PB-217 761

METHODOLOGY FOR ECONOMIC EVALUATION OF MUNICIPAL WATER SUPPLY/WASTEWATER DISPOSAL INCLUDING CONSIDERATIONS OF SEAWATER DISTILLATION AND WASTEWATER RENOVATION

Bechtel Corporation
San Francisco, California

August 1970

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PB 217 761

Final Report

METHODOLOGY FOR ECONOMIC EVALUATION OF MUNICIPAL WATER SUPPLY/WASTEWATER DISPOSAL INCLUDING CONSIDERATIONS OF SEAWATER DISTILLATION AND WASTEWATER RENOVATION

Prepared for

OFFICE OF SALINE WATER and

FEDERAL WATER QUALITY ADMINISTRATION

U.S. Department of the Interior

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August 1970

BECHTEL

FOREWORD

This report was prepared by the Bechtel Corporation for the Office of Saline Water and for the Federal Water Quality Administration; it is submitted as the final report in compliance with OSW Contract Number 14-01-0001-2161.

The report incorporates the results of an investigation to develop computational procedures for determining least-cost water supply and wastewater disposal systems for metropolitan areas. Special attention was given to seawater distillation and wastewater renovation in such determinations. The feasibility of the computational procedure (a mathematical model) was tested by application to a hypothetical coastal city.

Bechtel Corporation gratefully acknowledges the assistance provided by Mr. E. F. Miller of OSW and Mr. Robert Smith of FWQA during the course of this investigation.

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Section 1

INTRODUCTION AND SUMMARY

Section 1

INTRODUCTION AND SUMMARY

Increases in population, industry, agriculture, and recreation are imposing increased demands on conventional water sources. Since these water sources are not unlimited, it is becoming increasingly important for certain municipalities to consider the use of distilled seawater and/or renovated wastewater as alternate sources of additional water. The purpose of this study was to develop a methodology for determining the least-cost plan for using waters from such alternative sources.

The basic elements considered in developing the methodology are illustrated in Figure 1-1. These elements include treatment requirements for conventional water, seawater, and wastewater, as well as the storage and conveyance requirements. Also considered were the requirements for wastewater treatment and disposal which would be required in those cases where renovated wastewater is not used as a water supply source. The methodology was developed to determine the least-cost use of these elements in the context of an overall municipal water supply and wastewater disposal system.

Presented in the following portions of this section are the objectives, scope of work, summary, conclusions, and recommendations based on this investigation.

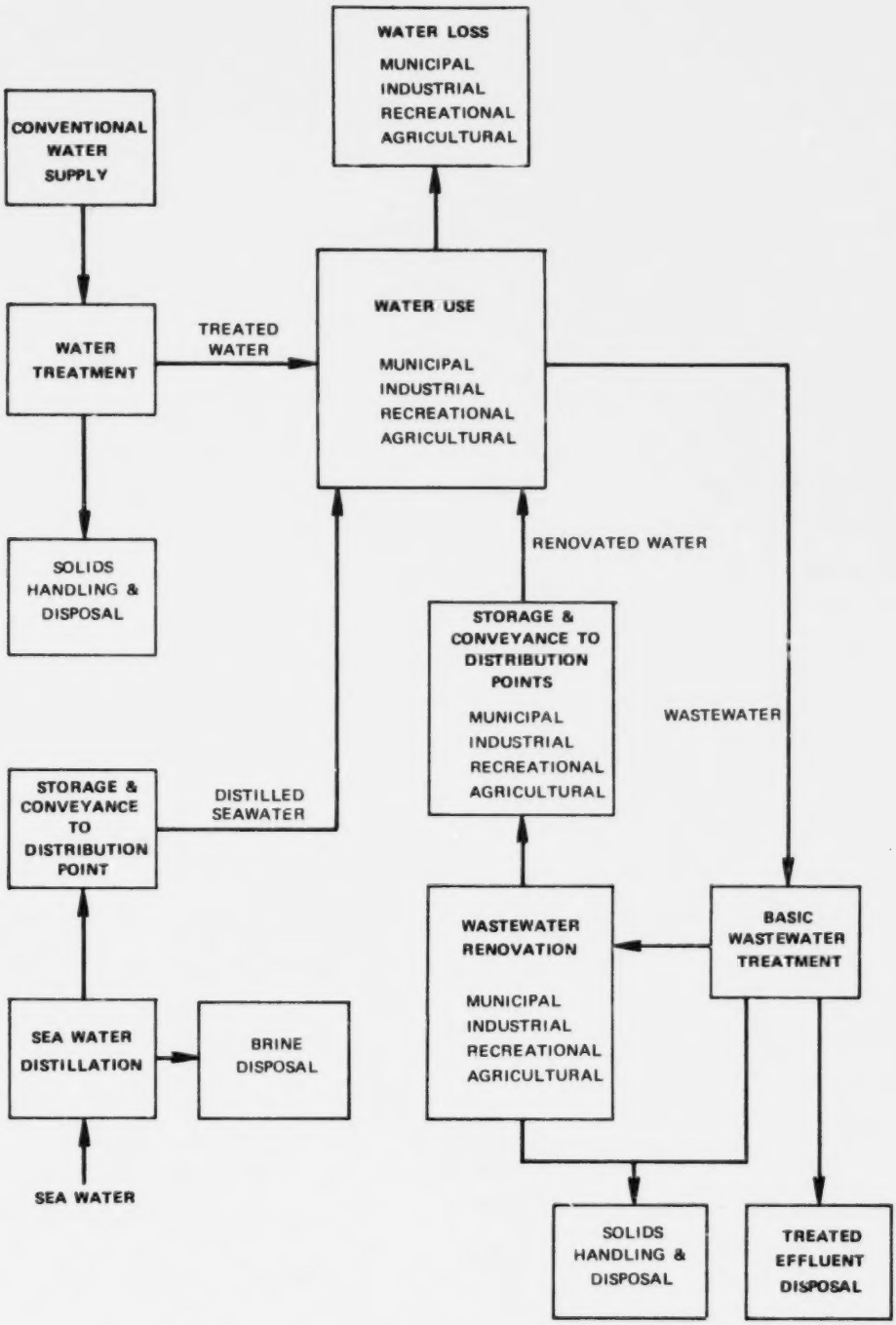


Figure 1-1. Basic Elements in Water Supply and Wastewater Disposal Systems

OBJECTIVES

The primary objectives of this investigation were as follows:

- To develop a computerized mathematical model which could be used as a tool for selecting the most economical water supply/wastewater disposal system
- To illustrate the use of such a model by performing test computations on a hypothetical water planning case where seawater distillation and wastewater renovation were considerations

SCOPE OF WORK

The work carried out during the course of this project included the following:

- Development of a mathematical model that can be utilized in determining the least-cost alternatives for meeting major water demand and wastewater disposal requirements within a metropolitan area
- Adaptation of the mathematical model to high-speed computer use in order that the cost associated with many alternative water supply/wastewater disposal systems can be analyzed within a reasonably short time
- Specification of cost data for the numerous elements found in an overall water and wastewater system. These costs were used in testing the developed methodology.
- Construction and solution of a hypothetical water planning problem to illustrate the use of the mathematical model

SUMMARY

The work presented in this report will be summarized under the following major headings: (1) Problem Discussion, (2) Network Model Description, (3) Cost Estimating Methodology and Basic Cost Data, and (4) Testing of the Network Model.

Problem Discussion

Section 2 of this report presents a discussion of the basic problem to be solved in planning a water supply/wastewater disposal system. It also provides a simple hypothetical example to illustrate the complexity of the problem, as well as possible approaches that may be employed in solving the problem.

Network Model Description

Based on the considerations presented in Section 2, the network model approach was selected for use in this study. The development and use of this model are presented in Section 3 using illustrative examples. The mathematical model is comprised of three basic components: (1) the preprocessing program, (2) the network program, and (3) the recosting program – all of which are described in the report.

Section 3 also presents a discussion on the factors that normally require consideration in setting up a network for a municipal area. Quality criteria, treatment requirements, and water blending are discussed, as well as the model capabilities and limitations.

Cost Estimating Methodology and Basic Cost Data

Cost estimating methodology and cost data are treated more fully in Section 4 of this report. The methodology and cost data presented in this section were used only for testing of the mathematical model and, therefore, are not specifically applicable to any particular problem.

The bases of the cost data are discussed, with particular regard to adjustment in price levels, capital costs, operation and maintenance costs, and

system administration and external costs. Based on this information, generalized cost data were developed for the major elements in water supply and wastewater disposal systems.

Testing of the Network Model

An illustrative water planning example was developed to show the application of the network model. This example utilized a hypothetical community with municipal, industrial, and agricultural demands which could be supplied by conventional water, renovated wastewater, and/or distilled seawater. Alternative conveyance systems connect the various demands and sources. The network model was then applied to the hypothetical example to find the most economical water supply/wastewater disposal system. A detailed description of the model structure and computer calculation is presented in Section 5.

CONCLUSIONS

This investigation resulted in the development of a computerized mathematical model that uses the network analysis theory as a basis for analyzing complex water and wastewater systems. The following conclusions are based on the results of this study:

- The network model developed can be a valuable tool for city and regional planners for selecting the least-cost water supply/wastewater disposal system in a municipal area.
- The model can be applied to new undeveloped areas and/or used for analyzing existing water and wastewater systems. Engineering judgement can be incorporated into the model structure with regard to water treatment requirements, plant locations, and conveyance routes.

- Based on test computer runs, the costs for conveyance of water and wastewater are a critical economic factor, which can significantly affect the feasibility of the use of an available water source. These factors require special studies for each location under consideration.
- The standard linear programming model was investigated but not selected for use in this study since the structure of the basic problem to be solved was more adaptable to the network model approach. The network model also required less computer time and the input data are much easier to utilize.

RECOMMENDATIONS

It is recommended that additional work be carried out in the following areas:

- Improving the cost efficiency of the computer model
- Extending the scope and capability of the program
- Utilizing the model for in-depth studies of specific municipalities.

Efforts to improve the cost efficiency of the computer program should probably be directed toward the preprocessing and recosting procedures in the model. It is believed that these procedures can be streamlined to significantly reduce the overall computer time required for a complete run. It would also be desirable to revise the data input formats to provide more flexibility in the choice of cost elements. The program output section can also be developed to furnish more information on specific cost items grouped by type and location and to automatically provide parametric information on key variables.

Extensions of the present model capabilities would be desirable with respect to the following specific items:

- Time Staging and Overcapacity Factors. An effort should be made to develop a procedure by which problems related to staging and design capacities of various facilities can be evaluated and accounted for in the establishment of a least-cost system. Both the possibilities for carrying this out within the computer model and as an external procedure should be considered. In this effort it would be desirable to use separate cost functions for capital and operating costs.
- Quality Parameters. In using the present mathematical model, water quality requirements are considered by specifying the minimum degree of treatment for each type of water source. The development and incorporation of a more direct method for specifying quality parameters in the model structure would be desirable. This may possibly be handled by employing subroutine procedures in conjunction with materials balance techniques.
- Conveyance Costs. The importance of conveyance costs, as indicated in this study, would justify developing formalized methods for determining such costs more accurately; consideration would be given to the specific characteristics and constraints associated with each individual conveyance routing. The very large number of factors that must be considered indicates the desirability of a computer approach that could be performed in a separate program or as a function of the preprocessing program of this model.
- Evaluation of Model Concept and Computational Results. A more formal comparison should be made of the concep' and computational results developed in this study with other optimization procedures (for example, process linear programming). In this comparison, it would be desirable to establish more firmly the mathematical optimality as generated by the present approach.

Finally, it is recommended that the procedures developed in this report be applied in in-depth studies of selected municipalities. Such studies should be performed in close conjunction with city and regional planners so that the results would be directly applicable to a given city. Such applications would, it is believed, establish more firmly the utility of the procedures discussed in this report.

Section 2

PROBLEM DISCUSSION

Section 2

PROBLEM DISCUSSION

The basic problem faced in this investigation was the development of techniques for economically evaluating the use of desalted seawater, renovated wastewater, and conventional water sources in the context of an overall municipal water supply/wastewater disposal system. In this section, certain issues for consideration in such analyses are presented, followed by discussions of possible computational procedures.

ISSUES FOR CONSIDERATION

There are many elements which enter into the economic analysis of alternative water sources for a municipal area. This is particularly true where the newer technologies of seawater desalting and wastewater renovation are to be considered. A very simple system of water supply and demand alternatives is shown in Figure 2-1 and discussed below to illustrate the complexity involved in analyzing even such a simple system.

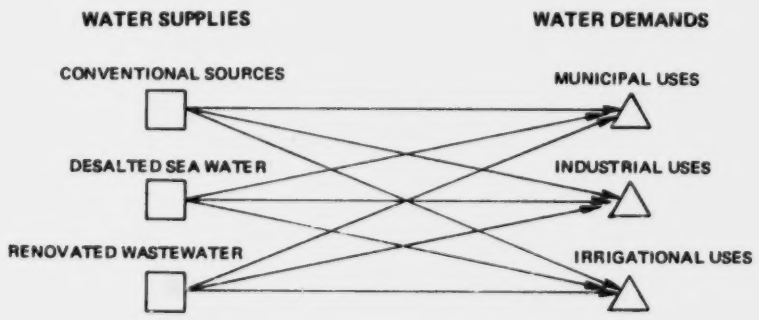


Figure 2-1. Example of a Simplified Water Supply System

Associated with each of the water supplies shown in Figure 2-1 are cost, quality, and availability factors. Likewise, each demand has certain quantity and quality requirements. If it is assumed, for example, that high-quality inexpensive conventional water sources are in ample supply, the problem solution is relatively trivial. However, there are coastal and other areas where conventional water sources are marginal, both in terms of quality and quantity, and, therefore, require economic consideration of numerous supply alternatives.

Shown in Table 2-1 are the basic groundrules for several hypothetical water planning examples based on Figure 2-1. Also shown in this table are elementary "solutions" for the examples based on the interrelationships between specified water costs, quality, availability, demand, and pollution control regulations. The complexity involved in such a simple system of only three water sources and three demands serves to illustrate the much greater complexity of a large municipal system. To further add to the intricacy of water planning problems are such additional factors as the following:

- The type and degree of treatment required for all available water sources, including seawater and wastewater
- Economics of scale associated with all elements in an overall water supply/wastewater disposal system
- Conveyance, storage, and distribution systems for renovated wastewater, distilled seawater, and conventional water
- Wastewater collection systems and the effect of wastewater renovation plant locations on this system
- Disposal of sludges, brines, and other residuals resulting from the operation of the treatment facilities
- Current and projected water pollution control regulations
- Effect of water quality criteria on possible water uses

Table 2-1

HYPOTHETICAL WATER PLANNING EXAMPLES

		Groundrules			
		Case 1	Case 2	Case 3	Case 4
Water Demands (mgd)					
Municipal		50	50	50	50
Industrial		40	40	40	40
Irrigational		10	10	10	10
Water Availability (mgd)					
CW		80	80	80	80
RWW		30	30	30	30
DSW		∞	∞	∞	∞
Water Costs (¢/1000 gal)					
CW		10	30	10	10
RWW		20	20	20	8
DSW		50	50	50	50
Water Quality (TDS in mg/l)					
CW		800	800	800	800
RWW		1200	1200	1200	1200
DSW		25	25	25	25
Major Constraints		None	Municipal water ≤400 mg/l TDS	Renovated wastewaters are not to be used for municipal use	(1) Industry requires water of ≤100 mg/l TDS (2) Tertiary treatment of wastewaters required by law
Water Demands	**Water Supplies**	"Possible Solutions" (mgd)			
		Case 1	Case 2	Case 3	Case 4
Municipal					
	CW	50	25	50	20
	RWW	-	-	-	30
	DSW	-	25	-	-
Industrial					
	CW	30	10	30	4
	RWW	10	30	10	-
	DSW	-	-	-	36
Irrigational					
	CW	-	10	-	10
	RWW	10	-	10	-
	DSW	-	-	-	-

Note: CW = Conventional water
RWW = Renovated wastewater
DSW = Desalted seawater

ADVANCED COMPUTATIONAL PROCEDURES

Because of the high degree of complexity associated with the analysis of large municipal water supply/wastewater disposal systems, it becomes apparent that advanced computational procedures are desirable in solving such problems. Such procedures are generally adaptable to high-speed computer technology and can be used with mathematical models describing the problem to be solved. The following is a discussion of several computerized mathematical modeling approaches considered during this study.

Linear Programming Model

Among the more advanced techniques for solving problems such as discussed above is the linear programming model. During this study, a limited-scope standard linear programming model was developed; the results of this part of the study are summarized in Appendix A. In general, it was discovered that the problem structure was more adaptable to the network model to be discussed later.

Nonlinear Programming Model

Since most of the cost functions associated with the problem to be solved are nonlinear, consideration was given to a nonlinear programming model. In recent years, there has been a great deal of research attention given to this programming approach, but, unfortunately, an efficient solution procedure is not presently available for general nonlinear problems. Progress has been made in developing solutions for a few special cases, but these cannot be readily adapted to the problem of concern at this time. For this reason, additional consideration was given to the network model, which was adapted to accommodate nonlinear cost functions using iterative procedures.

Network Model

Network models have long been used for analyzing complicated network systems, particularly in the field of electrical distribution. This analytical tool has also found use in analyzing transportation systems, information theory, and the planning and control of research and development projects. The problem of allocating various sources of water to meet specific demands at a minimum cost is the fundamental problem encountered in this study and is, therefore, adaptable to network theory.

The network model to be discussed in detail in the following section is a particular type of linear programming model. For general linear programming models, the so-called "Simplex" method is the one associated with solving these linear programming problems. However, the method of solution associated with the network model is much more efficient than the simplex method, requiring less time to formulate the input data and less computational time to obtain an optimal solution. For these reasons, the network model was the approach selected to solve the problem of concern.

Section 3

NETWORK MODEL DESCRIPTION

Section 3

NETWORK MODEL DESCRIPTION

As noted in Section 2, a network model was selected in this study for use as the basic planning tool for water supply/wastewater disposal systems. In this section, a description is given of the model developed, as well as information on its use in water planning. Also discussed are the capabilities and limitations of the model.

NETWORK DESCRIPTION

In structuring a network to represent the water supply/wastewater disposal system for a municipal area, an "arc," or line, is assigned for each function or activity in the system. For example, an arc would be used to represent a treatment process, or group of processes, and each conveyance route between a source and a demand. Each end of every arc is then given a designation [i.e., letter(s) and/or number(s)] and is termed a "node." By connecting all the arc nodes of a complete system, such that treatment processes and conveyance routes are in a technically feasible sequence, a network is formed. In this process, it is important to understand that the same node can represent the source end of one arc and the demand end of a connecting arc.

An example of a very simple network is shown in Figure 3-1 to illustrate these concepts as applied to the simplified example presented in Section 2.

For each arc used in a network, there is a unit cost (cents/1000 gal.) assigned. The basic objective in analyzing a network is, therefore, to

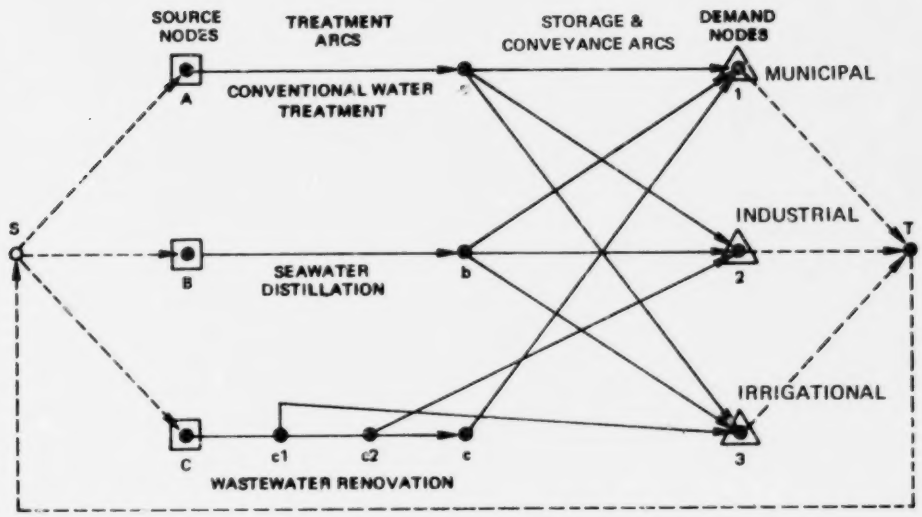


Figure 3-1. Sample Network to Illustrate Arcs and Nodes

find the flow in each arc, zero or otherwise, which will minimize the total system cost and at the same time satisfy all of the supply and demand constraints. The network program discussed below is designed to make such an analysis of very complex networks. Other components in the network model are "preprocessing" and "recosting" programs, which are also described in this section.

Network Program

The network program, which is the primary component in the mathematical model, is a general purpose program originally developed by Professor Gene Woolsey of the Colorado School of Mines. It was obtained by Bechtel without fee through the General Electric Program Library in Phoenix, Arizona.

The network program, which is based on an integer linear programming method, has the following capabilities for analyzing various types of network problems:

- A shortest path algorithm, from one node to all others
- A maximum-flow, minimum-cut algorithm
- An out-of-kilter algorithm
- A minimal spanning-tree algorithm

The out-of-kilter algorithm is applicable to the problem to be solved here. The original program was capable of analyzing a network containing 25 arcs. However, it was expanded during this study to analyze 1000 arcs and was integrated with the preprocessing and recosting programs to be discussed later.

Using the out-of-kilter algorithm in the network program, the unit cost data generated for each arc in the system by the preprocessing program, along with the constraints for each arc, are analyzed in accordance with the network theory given in Appendix B. In general terms, flows are allocated to each arc in the network by the program, and a possible flow pattern is generated. Starting from the source node, prices for the water or wastewater in the direction of flow are computed at each node on the flow pattern. These prices reflect the cumulative arc costs to the terminal node in question and are designated "node prices."

Following the above procedure, the program checks the feasibility of the solution by determining if all demands are met and all constraints are satisfied. Next, the network program determines if optimality conditions are satisfied in each arc and if the solution is optimal. The relative values of the node prices on the two extremities of an arc, the arc cost, and the flow define an optimality condition as explained in mathematical terms in Appendix B. If the solution is feasible and optimal conditions in any arc are satisfied, the flow in that arc is considered as a possible solution in further analysis (i.e., the arc is "in-kilter"). The model then goes through the network and finds an arc that does not meet the feasibility and optimality conditions

(i.e., arcs that are "out-of-kilter"). The flows in these arcs are then changed by using a flow circulation technique in order to establish feasibility and optimality conditions. At the same time, those arcs previously "in-kilter" are reexamined to be certain they do not go "out-of-kilter." This process is repeated until all arcs in the network are being used in a feasible and optimal way, in which case the solution is feasible and represents the minimum cost.

In applying the network model, an important aspect that must be incorporated into the model structure is that of interconnecting all sources with all demands in order to establish a closed loop cycle. This concept is illustrated for the sample network shown in Figure 3-1, where it can be seen how all sources originate from a common node, S, all demands terminate at a common node, T, and the nodes S and T are connected by a return arc. This approach, in which only one type of flow conservation equation is required, eliminates the need to formulate a separate equation for each source and demand point in the network. The demands are specified by using constraints on the minimum allowable flow in the arcs connecting the demand nodes with the terminal node T; the availability of various sources is specified by using constraints on the maximum allowable flow in the arcs connecting the common node S with the source nodes. Further discussion on the use of the model will be presented later in this section of the report.

Because of the nonlinearity of the unit cost data, as pointed out in Section 2, the optimum flows determined by the first pass through the network program will, in general, not be the least-cost solution. To account for the nonlinear cost functions and to formulate the input data in the correct format, an iteration procedure was developed which uses a preprocessing program and a recosting program in conjunction with the network program as discussed in the following paragraphs.

Preprocessing Program

During this study, the preprocessing program was developed to calculate unit costs for each of the arcs associated with the network being studied.

The unit costs for most activities in a network are nonlinear with respect to the flow rate, as illustrated in Figure 3-2. Since the network program does not directly consider these nonlinear functions, it was necessary to determine the unit cost for each arc outside the network program using the preprocessing program.

In developing the preprocessing program, the unit cost for each activity in a network was equated to the flow rate and included in the program. From the input data, the preprocessing program is designed (1) to select the unit cost equation(s) applicable to the activity represented by each arc and (2) to calculate, using the developed cost functions, the unit cost based on the specified flow rate. The development of the cost functions and the data used in the program are presented in Section 4.

Since the network program is based on an integer linear programming model, all data required by the network program are converted to integers by the preprocessing program. In doing this, the numerical values of the unit cost data are converted to integers representing the nearest one-hundredth of a cent per thousand gallons and the flow rate data are converted to the nearest one-tenth of a million gallons per day (mgd).

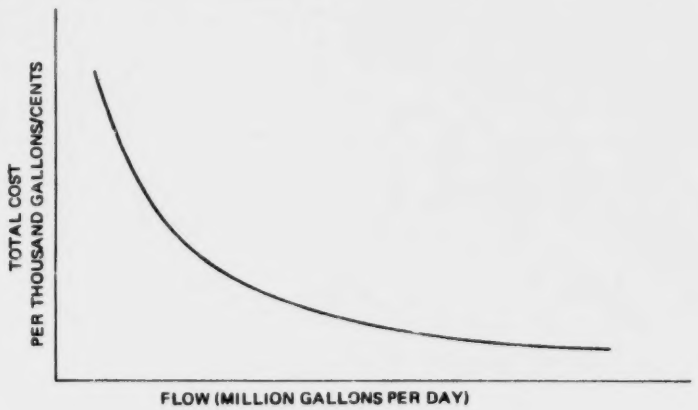


Figure 3-2. Arithmetic Plot of Typical Nonlinear Cost Function

Recosting Program

The recosting program has been developed to perform the following tasks:

- To calculate the total cost for the network. This cost is based on the initial unit costs calculated in the preprocessing program and the flows generated by the network analytical program.
- To reassign the flows from the network program to the initially assigned flows in the input data. The preprocessing program then calculates the new unit costs that are used again in the network program. From the flows and unit costs obtained from the second pass through the model, the recosting program calculates a new total cost for the network.
- To calculate the percent change in the total network costs between the first and second times through the model. If the percent change in total costs is greater than a fixed value – in this study, two percent was used – the recosting program again reassigns the new flows to the preprocessing program and a new cycle starts.

The above iterative procedure takes into account the nonlinear cost functions discussed earlier. The criterion for stopping the iterations (i.e., when the total system costs change less than two percent from the previous time through the network) was met in all cases studied after four iterations. And generally, the total costs for the last two iterations were the same, thus indicating that the solution was indeed optimal. The recosting program was designed to automatically stop after five iterations in order to avoid the use of excessive computer time in the event a mistake had been made in the input data. When the above criteria are met, the unit cost for each arc, the flow in each arc, and the total network cost for each iteration are printed.

Generalized Flow Diagram of Network Model

Shown in Figure 3-3 is a generalized flow diagram illustrating the basic network model components and their fundamental use when employed in analyzing a municipal water supply/wastewater disposal system. This diagram is not intended to illustrate every function in the model but rather to summarize the preceeding discussions on the network, preprocessing, and recosting programs. A complete listing of the network model program is given in Appendix C.

The importance of engineering judgment in applying the network model is also apparent in Figure 3-3. This aspect is used in defining the initial conditions for the model and the need for system changes. The concept of providing for such judgment in structuring the network and in evaluating the results generated has been given major emphasis in this study. It is felt that in this manner the model emerges from the realm of being purely hypothetical and is given a realistic basis applicable to a particular water supply/wastewater disposal system.

NETWORK MODEL USE

The factors that must normally be considered in using the network in municipal water/wastewater planning are presented in this part of the report. A general discussion on the development of quality criteria and treatment requirements is presented. Also, the input data required for the network model are discussed as well as an example illustrating its use.

Background Information

Closely associated with the use of the network model is a physical concept of the city or metropolitan area under consideration. In the development on this concept, the problem scope is defined in terms of population and flow projections, location of major facilities, and quality criteria.

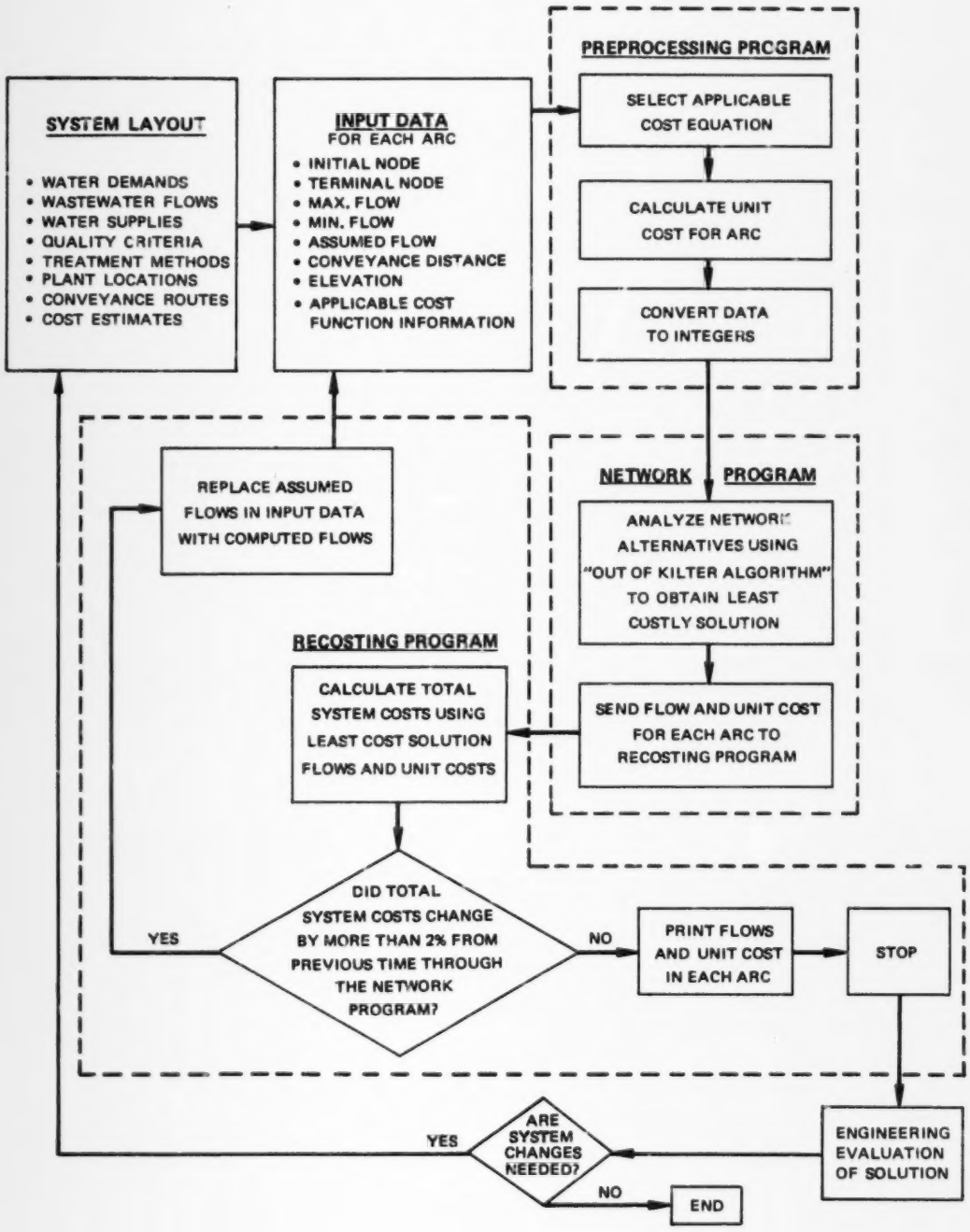

SYSTEM LAYOUT
• WATER DEMANDS
• WASTEWATER FLOWS
• WATER SUPPLIES
• QUALITY CRITERIA
• TREATMENT METHODS
• PLANT LOCATIONS
• CONVEYANCE ROUTES
• COST ESTIMATES
INPUT DATA
FOR EACH ARC
• INITIAL NODE
• TERMINAL NODE
• MAX. FLOW
• MIN. FLOW
• ASSUMED FLOW
• CONVEYANCE DISTANCE
• ELEVATION
• APPLICABLE COST FUNCTION INFORMATION
PREPROCESSING PROGRAM
SELECT APPLICABLE COST EQUATION
CALCULATE UNIT COST FOR ARC
CONVERT DATA TO INTEGERS
NETWORK PROGRAM
ANALYZE NETWORK ALTERNATIVES USING "OUT OF KILTER ALGORITHM" TO OBTAIN LEAST COSTLY SOLUTION
SEND FLOW AND UNIT COST FOR EACH ARC TO RECOSTING PROGRAM
RECOSTING PROGRAM
CALCULATE TOTAL SYSTEM COSTS USING LEAST COST SOLUTION FLOWS AND UNIT COSTS
REPLACE ASSUMED FLOWS IN INPUT DATA WITH COMPUTED FLOWS
DID TOTAL SYSTEM COSTS CHANGE BY MORE THAN 2% FROM PREVIOUS TIME THROUGH THE NETWORK PROGRAM?
YES
NO
PRINT FLOWS AND UNIT COST IN EACH ARC
STOP
ENGINEERING EVALUATION OF SOLUTION
ARE SYSTEM CHANGES NEEDED?
YES
NO
END

Figure 3-3. Model Components

Before the network model can be used, background information on the following items must be obtained in order to structure the network so that it represents the area being studied:

- Population estimates for the year being investigated
- Water demands in terms of quantity, quality, and location
- Wastewater flows in terms of quantity, quality, location, and availability
- Water supplies in terms of the type of source, quality, and availability
- Location of existing and proposed facilities
- Conveyance routes existing and proposed
- Unit cost information for each activity in the network
- Quality criteria and treatment requirements

Population Estimates

Population projections, such as those available from municipal planning departments, water and sanitary districts, and state and federal agencies, should be reviewed and the population growth projected for the period of study.

Water Demands and Wastewater Flows

The accuracy of the solution from the network model depends to a great extent on the accuracy of the input data on the water and wastewater flows, which are related to the population projections. Normally, establishment of the necessary data requires a detailed study of existing engineering and other reports, site visits, and discussions with local and state controlling agencies.

Municipal Water Demand. Municipal water demands generally include residential, commercial, small public parks, and light industrial water demands. These demands are estimated on the basis of total projected population and water requirements per day per capita. The estimated flows can be subdivided into the individual demands for use in the model by identifying logical subdivisions in the existing or projected water distribution system.

Industrial Water Demand. This includes demands for large scale industrial users and major industrial complexes. In many cases, estimates of these demands are not readily available. Therefore, projections from the present demands in direct ratio to the population increase can frequently be used to estimate future demands. Two types of industrial water quality were considered in this study – cooling water and high-quality industrial process water.

Agricultural Demand. The agricultural demands can be estimated on the basis of acreage, type of crop, and available rainfall, as indicated in published reports.

Noncrop Irrigation Demand. This group includes projected demands for irrigation of such features as major regional parks, college campuses, golf courses, and airports. The water demands are generally determined using the same bases used for agricultural demands.

Wastewater Flows. Wastewater flows for disposal or renovation can be identified at selected points in the main trunk sewer system for each city studied. The amount of flow at these points can be estimated on the basis of the contributing population. Generally, available data can be used to determine the percentage of the water demand returned to the wastewater collection system.

Water Supplies

The estimated amount of water available from various water resources serving the region to be studied may be obtained from published reports of the agencies involved. Sources include water from state and regional water development projects, local impoundments, and well systems. The network model can be structured to account for the types and quantities of water sources available.

Location of Facilities

In defining the physical system layout, the location of all major existing water and wastewater conveyance and treatment facilities should be identified. Projections for the addition of new facilities should be considered. In structuring the network model, engineering judgment can be incorporated into the selection of sites for potential treatment plants and conveyance routes, which are then analyzed using the network model.

Potential sites for wastewater renovation plants may be selected along main trunk sewers after estimating the wastewater flow available for renovation at various locations. Also, consideration should be given to existing wastewater treatment plant sites which might be used for construction of new facilities. In addition to the available flows, the relative proximity of the treatment plants to the water demands should be taken into consideration in an attempt to minimize conveyance requirements.

Sites for seawater distillation plants should be selected near a seawater source so that seawater conveyance and brine disposal costs are minimal. As with the wastewater renovation plants, the relative proximity of the distillation plants to the water demands should be considered in an attempt to minimize conveyance requirements.

Conveyance

For each potential water source and demand, various types of conveyance routes can be specified as follows:

- Type A: heavily congested areas (downtown city areas)
- Type B: moderately congested areas (residential, light commercial)
- Type C: lightly congested areas (farmland, undeveloped areas

Since the municipal demands are not point demands, the conveyance requirements can be determined from consideration of the existing or proposed treated water distribution system with one or more suitable tie-in points identified on main water lines. For the larger industrial areas and the noncrop irrigational demands, an allowance can be made in the conveyance distance to include costs of the minor distribution system required within these areas. Elevation differences should be specified to the midpart of the demand system rather than to the tie-in point, and then added to the pumping head required for each conveyance route.

Unit Cost Information

Cost estimation methodology and basic cost data are discussed in detail in Section 4.

Quality Criteria and Treatment Requirements

The quality aspects of water supplies and wastewater discharges are defined as part of the network structure, external to the actual computational

procedure. Considerations of water quality fall into two classes: (1) those concerned with discharges of wastewater and receiving water quality, and (2) those concerned with the quality required for specific uses of water. In the latter group, the possibility of upgrading existing water quality by blending with water of higher quality can also be considered, as discussed later.

Since the water use requirements for any city depend upon numerous factors, they necessitate an in-depth investigation for each specific case. Following such an investigation, treatment requirements which relate the type of water source and its treatment to specific water demand quality requirements can be incorporated into the network structure. During this study, generalized treatment requirements were specified for various types of water sources for demands requiring different qualities. To illustrate this concept, Figure 3-4 shows the treatment requirements for conventional water sources, wastewater renovation, and seawater distillation, as used (in Section 5) during the testing of the network model.

Wastewater Discharges and Receiving Water Quality. The criteria and treatment requirements associated with this group are highly dependent on the specific location, beneficial uses, and available dilution of the receiving water. Treatment schemes which satisfactorily meet the pollution regulations can be incorporated into the network model. For example, before wastewater is discharged in enclosed estuarine areas, phosphorus and nitrogen removal can be specified in the network structure in addition to secondary level treatment.

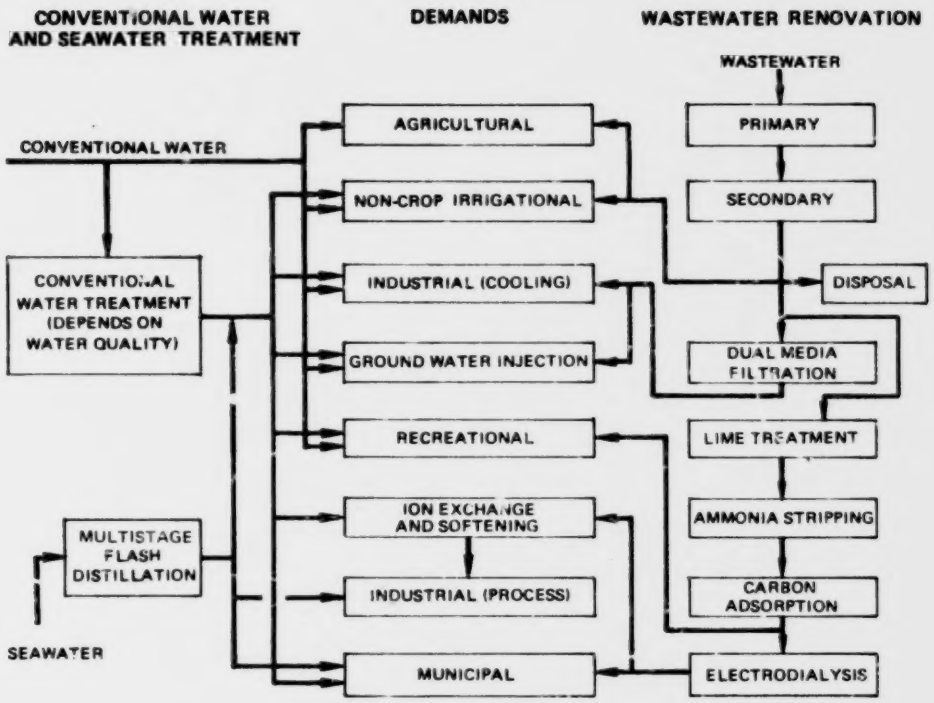


Figure 3-4. Water Treatment Requirements Used in Network Model

Input Data

The following is a discussion of the input data and their use in the network model. The input data for each arc in the network contain the information shown in Table 3-1. A separate data card is prepared for each arc in the network. On each card, columns 1 through 36 contain information related to the supply (initial) and demand (terminal) node designations, constraints on the allowable flows, the assumed flow initially used in the preprocessing program to calculate the unit cost, and locational aspects of the activity represented by each arc. In the event the minimum flow constraint is zero, card columns 17-20 remain blank. When an arc is not related to conveyance costs, card columns 21-36 also remain blank.

Table 3-1

INPUT DATA FORMATS

Card columns 1-4	=	initial node
Card columns 5-8	=	terminal node
Card columns 9-12	=	maximum flow constraint, mgd
Card columns 13-16	=	minimum flow constraint, mgd
Card columns 17-20	=	assumed flow, mgd
Card columns 21-24	=	distance, type A (miles)
Card columns 25-28	=	distance, type B (miles)
Card columns 29-32	=	distance, type C (miles)
Card columns 33-36	=	delta elevation (feet)

Input the following items with a value 1 if that item is included in the cost calculations. Otherwise, leave the item blank.

Card column 37	=	flow addition (used when arc unit cost equals zero)
Card column 38	=	municipal source development and raw water conveyance
Card column 39	=	agricultural source development and raw water conveyance
Card column 59	=	surface water treatment without softening
Card column 60	=	ground water treatment with chlorine
Card column 61	=	ground water treatment with demineralization
Card column 62	=	surface water treatment with softening
Card column 63	=	primary treatment
Card column 64	=	primary and activated sludge treatment
Card column 65	=	dual media filtration
Card column 66	=	phosphorus and nitrogen removal, and carbon adsorption
Card column 67	=	electrodialysis
Card column 68	=	primary and trickling filter treatment
Card column 69	=	carbon adsorption
Card column 70	=	phosphorus and nitrogen removal
Card column 71	=	ground water injection
Card column 72	=	wastewater conveyance
Card column 75	=	seawater distillation
Card column 76	=	treated water conveyance
Card column 77	=	industrial water treatment using softening and ion exchange
Card column 78	=	treated water storage based on a fixed detention time of the average flow (6 hr)

The data card columns 37-80 are used to identify or flag the cost function(s) in the preprocessing program that apply to one or more specific activity represented by the arc. For example, assume an arc represents the processes of activated sludge treatment and dual media filtration. To relate this information to the preprocessing program, the number 1 would be placed in card columns 64 and 65 and the preprocessing program would select the unit cost equations to be used in the calculations that correspond to these processes. As can be seen in Table 3-1, all the card columns from 37-80 do not have specific designations. The columns that are not designated can be used whenever new or different cost functions for a particular network are needed.

Example Network Problem

In order to further illustrate the use of the network model, an example is presented to demonstrate how the input data can be set up for a network. The simple network shown in Figure 3-1 will be used for this example. The information given in Table 3-2 will be used in the example to illustrate the use of constraints related to specific arcs.

Table 3-2

INPUT DATA USED IN EXAMPLE NETWORK

Water Source Node & Type	Water Source Availability	Water Demand Node & Type	Water Demand Flow
A – Conventional	30 mgd	1 – Municipal	20 mgd
B – Seawater	∞	2 – Industrial	10 mgd
C – Renovated Wastewater	15 mgd	3 – Irrigational	5 mgd

The following Table 3-3 shows how the input data for the example would be used. For this example, three arcs have been shown to represent various degrees of wastewater renovation. In some cases where several unit processes are used in series and water of intermediate quality from the series is not required, one arc can be used to represent all of these processes by flagging the appropriate cost functions in the preprocessing program, as illustrated in the example. Also shown in Table 3-3 are conveyance distances and differences in elevation plus pumping head assumed for the example, as well as the input data card columns (Table 3-1) that were used to flag the unit cost function for each arc in the network. Where the maximum flow can be infinite or is constrained by preceding arc constraints, a value of 9999 mgd is used in the input data.

Table 3-3

EXAMPLES OF INPUT DATA USE

Initial Node	Terminal Node	Max. Flow, mgd	Min. Flow, * mgd	Assumed Flow, mgd	Distance Type A, Miles	Distance Type B, Miles	Distance Type C, Miles	Elevations Feet	Add Value i To Input Card Column **
S	A	30	-	20	-	-	-	-	38
S	B	9999	-	10	-	-	-	-	37
S	C	15	-	10	-	-	-	-	37
A	a	9999	-	20	-	-	-	-	59
B	b	9999	-	10	-	-	-	-	75
C	c1	9999	-	10	-	-	-	-	64
c1	c2	9999	-	10	-	-	-	-	65
c2	c	9999	-	10	-	-	-	-	66, 67
a	1	9999	-	15	2.0	1.3	-	100	76
a	2	9999	-	5	-	2.0	1.0	120	76
a	3	9999	-	1	-	1.0	3.0	210	76
b	1	9999	-	5	1.0	2.0	-	150	76
b	2	9999	-	5	-	1.0	1.0	100	76
b	3	9999	-	1	-	-	2.0	50	76
c	1	9999	-	1	1.5	0.5	-	125	76
c2	2	9999	-	5	-	1.5	1.0	200	76
c1	3	9999	-	5	-	0.5	2.0	110	76
1	T	20	20	20	-	-	-	-	37
2	T	10	10	10	-	-	-	-	37
3	T	5	5	5	-	-	-	-	37
T	S	9999	-	-	-	-	-	-	37

* Assumed flows are for the initial iteration only. The conservation of flow at each node is handled internally by the computer program.

** See Table 3-1 for cost functions flagged.

After the input data for each arc have been set up as illustrated in the example, the information is ready to be analyzed using the network model. The network model will determine the optimum flow in each arc, based on the unit cost data calculated in the preprocessing program using the assumed flow. The iteration procedure will also be used, in which event the assumed flows are replaced with the flows determined from the network program and new unit costs are calculated. This procedure continues until the total system cost does not change by more than two percent from the previous time through the model, at which time the model solution is printed.

Not illustrated in the example is the procedure used to handle existing treatment and conveyance facilities. However, this can be handled in the network structure using the following general procedure:

- First, specify an arc to represent each existing facility (e.g., treatment plant or conveyance route) and use a maximum flow constraint for the arc that equals the capacity of the existing facility. For this arc, a separate unit cost for operation and maintenance of the existing facility could be incorporated into the preprocessing program along with a designated column in the input data; however, this was not done in the present model.
- Second, specify an arc to represent each new facility parallel to the arc representing the existing facility. For this parallel arc, specify the maximum flow constraint and flag the appropriate cost function in the preprocessing program.

Blending for Quality Improvement

In many cases, the water quality of conventional water sources is less than desirable but can be improved by either providing additional treatment or blending with very high-grade waters. During this study, consideration

was given to the blending of distilled seawater with conventional water sources. At this stage in the development, the total dissolved solids (TDS) of the water was considered the critical quality parameter.

The approach used with the network model to accomplish this objective is outlined as follows:

- A network solution is initially obtained in which blending is not considered. From this solution, the water sources and the quantity used from each source can be determined.
- Secondly, required blending points in the network are specified and interconnected by a conveyance system to one or more seawater distillation plants.
- Next, the amount of conventional water and distilled water required at each blending point in order to provide water of a desired quality is calculated.
- In the network model, flow constraints are then placed on the arcs which supply conventional and distilled seawater such that the required blend will be forced in the final solution.
- Finally, the least-cost solution under the specified blending constraints using the network model is generated and compared to the total system cost when blending was not required.

The example network problem discussed above along with the network shown in Figure 3-1 will be used to illustrate the general approach for blending waters of different quality. Assume the solution from the example network problem resulted in 20 mgd of water being supplied to the municipal demand (20 mgd) from the conventional water source (i.e., arc "a 1"). Also assume the TDS of the conventional water source is 800/mg/l, the distilled seawater is 25 mg/l, and the desired water quality is 500 mg/l. From this information, a flow of 12.3 mgd should come from the conventional water source, and 7.7 mgd should come from the distilled seawater source. To assure this desired blend, set the maximum and

minimum flows (Table 3-3) in arc "a 1" equal to 12.3 mgd and arc "b 1" equal to 7.7 mgd. The input for the other arcs in this example would remain the same as shown in Table 3-3. The computer program would then be run again to obtain a solution and the resulting system cost would be compared with the computer run when blending was not required.

When more complicated networks are considered, all conveyance arcs leading from the conventional water sources to each demand point would be connected to an intermediate node adjacent to each demand point. This intermediate node would then be connected to the demand node by an arc and the flow constraints (i.e., max = min flow of conventional water required for blending) would be placed on this arc. A similar approach would be used for the distilled seawater sources in which the conveyance arcs from several distillation plants would be connected at an intermediate node, the intermediate node connected to the demand node by an arc (separate from the arc used for the conventional water sources), and the flow constraints on the amount of distilled seawater required for blending placed on this arc. This approach allows one to optimize the use of the conventional water sources and the distilled seawater sources while at the same time forcing a desired blend of water. It is important to realize, however, that since the water flows from these two sources were forced in the network using constraints, the entire network may not be optimized.

The above approach could also be applied in a study where demineralized renovated wastewater is considered. In either case, the network model can be used to evaluate the cost of blending water of different qualities to improve the overall quality.

NETWORK MODEL CAPABILITIES AND LIMITATIONS

The network model as presently developed can be used as a valuable tool by city and regional planners for selecting the least-cost water supply/wastewater disposal system in a municipal area. In doing this, many alternatives can be simultaneously analyzed within the context of an integrated water and wastewater treatment, storage, and conveyance system.

In using the model, the desired water quality for specific uses can be defined externally from the network program by specifying the degree of treatment required. This enables one to observe the effect on the system solution of either including or eliminating certain treatment processes, and also the effect on the total system costs. In addition, the economies of providing required treatment for large flows of wastewater followed by higher degrees of treatment for smaller flows to be used for specific purposes can be directly evaluated using the model.

Engineering judgment can be incorporated into the model structure with regard to treatment requirements, plant locations, and conveyance routes. The model can be used to evaluate alternative plant sites and conveyance routes in the context of an overall water supply/wastewater disposal system.

The cost of supplying water with improved quality characteristics can also be determined by forcing defined blends of water having different qualities. The model can be used to evaluate the type, size, and location of the treatment facilities required to provide such quality.

Parametric information can be obtained for those factors having a high degree of uncertainty simply by changing the appropriate cost equations in the model. For example, the model can be structured such that solutions can be generated for different interest rates on capital investment to see how this parameter may affect the selection of facilities. Similarly, the effect of decreased costs projected for advances in the technology of distillation or other treatment processes can be evaluated.

At the present stage of development, the preprocessing and recosting programs are relatively inefficient in the sense that several modifications for markedly decreasing the overall computer time requirements are possible in the computational procedure. This does not, however, affect the system solution. For analyzing a network consisting of approximately 280 arcs using a General Electric 635 computer, the cost is presently about $150.00.

Based on the inputs to the model that are related to a specific year, the model presented can be used to evaluate a least-cost system that will meet specific water and wastewater requirements. While existing facilities can be taken into account, the model does not solve staging of new facilities with respect to time. Because of the economies of scale, optimum staging is very important for obtaining adequate funding, purchasing land for the required facilities, conducting necessary research and development, performing detailed engineering, and completing construction at the proper time. However, the potential exists in the model for handling the staging problem either as an internal optimizing problem or by consideration of separate solutions obtained for a number of years.

Last, but certainly not least, the model does not incorporate direct considerations of the political, social, and psychological factors of the problem to be solved. Regardless of how logical and economical a particular solution may appear, its implementation can be limited severely by such intangible factors. To a certain degree, some of these factors can be incorporated in the initial model structure by specifying limiting constraints for the system under study.

Section 4

COST ESTIMATING METHODOLOGY AND BASIC COST DATA

Section 4

COST ESTIMATING METHODOLOGY AND BASIC COST DATA

This section describes the cost data used in Section 5 to illustrate the application of the mathematical network model. The data shown represent only a frame of reference from which detailed studies on water supply and wastewater disposal systems can be developed through more specific cost information. The costs were developed primarily from Office of Saline Water (OSW) information on the cost of seawater distillation and from Federal Water Quality Administration (FWQA) information on the cost of wastewater treatment and renovation processes. Additional data were derived from published papers in the professional literature and from Bechtel experience. The cost data were modified, as required, to ensure a common basis.

COST BASES

In general, the cost information presented represents "averages" in the sense that it is derived from a large amount of data and is not related to a particular city, plant site, or set of operating conditions. It is, however, sufficiently accurate to (1) illustrate the use of the mathematical model and (2) provide preliminary parametric information on the relative importance of the cost elements in a large-scale system that includes facilities for water supply, desalination, water renovation, and wastewater disposal. In a detailed study in which particular plant sites have been identified, it would be necessary to refine these data further and to develop additional cost information related to the selected sites before a final economic comparison and system optimization could be made.

A relatively conservative approach was taken in the development of the cost data, in that only proven processes and established treatment sequences were used. All cost data were based on July, 1969, price levels. Where necessary, data were adjusted to July, 1969, through the use of the various published indices as shown in Table 4-1.

Table 4-1

COST INDICES

Index	System Elements
FWQA Sewer Line Cost Index	Water and Wastewater Conveyance Systems
FWQA Treatment Plant Cost Index	Water and Wastewater Treatment Plants
U.S. Department of Labor Average Earnings for Nonsupervisory Workers in Water, Steam, and Sanitary Systems	Labor and Operating Costs

When considering systems for cities or metropolitan areas in various parts of the country, adjustment of the cost data may be necessary to account for differences in materials and labor costs. While this adjustment may be relatively minor compared to other variables, corrections can be made, if desired, by using the 20-cities index on treatment-plant cost and sewer-line cost compiled by the FWQA.

All cost data used are in the form of cents per thousand gallons of water or wastewater, and are variable depending on the flow rate. For a given flow rate, it was assumed that the cost would remain the same over the lifetime of the facility. The cost data represent actual production costs corresponding to a projected flow. They do not reflect under- or over-capacity flows that might occur in staged development schemes.

Discussed below are relevant points considered in developing capital, operating and maintenance, and system administration and external costs.

Capital Costs

As a rule, these costs include the total installed cost for all facilities and equipment of a particular system. Land acquisition and site preparation costs, owner administration costs, and interest during construction are included. For new facilities, an annual capital charge rate of 7 percent of the total capital was employed, but for conveyance systems, a 50-year life and a 5-percent interest rate were used, resulting in an annual charge rate of 5.4 percent.

Operation and Maintenance Costs

Operation and maintenance (O&M) costs include fuel, electricity, chemicals, supplies and maintenance materials, and O&M labor, as required by the individual facilities. Important groundrules utilized in the derivation of O&M costs are given in Table 4-2.

Table 4-2

GROUNDRULES FOR OPERATION AND MAINTENANCE COSTS

Item	Basis
Fuel	20¢ and 40¢ per 10^6 Btu for seawater distillation
Electricity	7 mills /kwh
Chemicals	$38/ton for sulfuric acid $10/ton for lime
Supplies and Maintenance Materials	(1) 0.5% per year of capital cost for seawater distillation (2) 0.25% per year of capital cost for conveyance systems
Operating and Maintenance Labor	(1) Based on OSW staffing estimates for seawater distillation (2) Included by FWPCA in water and wastewater treatment

System Administration and External Costs

This category includes the cost of administration and management of both the water supply and the wastewater disposal systems. External costs include charges for water supplied from outside the study area and charges for acceptance of wastewater into other disposal systems. Those cost items are, of course, unique for each municipality under investigation and can be best abstracted from published documents of the city.

COST ELEMENTS

Cost elements listed in Table 4-3 provide a reasonably complete list of cost items for most municipal water supply/wastewater disposal planning situations. Additional cost elements may be necessary in an in-depth study of a particular city when other treatment steps and process sequences are considered to be important. In some cases, the items shown are alternatives and will not necessarily apply to a given city or metropolitan area. For example, groundwater may not be available for use in one case, whereas in another it may be of utmost importance. Each cost element generally will be applied several times in an overall system, since most large cities will have, for example, more than one water treatment plant of a similar type.

Furthermore, several of the cost elements can be considered independently from the cost minimization process carried out by the network model. Costs related to existing facilities are among these. While the capacities and limitations of such facilities must be considered in the optimization model, their costs are fixed and can be added to the system costs following the selection of an optimal system.

Table 4-3

MAJOR COST ELEMENTS

Conventional Water Source Development	Statewide or regional aqueduct systems Local dams or diversion facilities Groundwater well fields
Water Treatment	Surface water treatment, conventional Surface water treatment, with softening Groundwater treatment, conventional Additional treatment for high-grade industrial use
Seawater Desalination	Multistage flash distillation
Wastewater Renovation	Activated sludge treatment (including primary treatment) Secondary effluent chlorination Lime treatment and ammonia stripping Sand filtration Carbon adsorption and filtration Electrodialysis Groundwater injection
Wastewater Disposal	Primary treatment followed by ocean outfall Activated sludge treatment Activated sludge treatment followed by lime treatment and ammonia stripping
Conveyance	Raw water conveyance Treated water distribution system Distilled and renovated water conveyance Wastewater collection system Wastewater conveyance (trunk sewers)
Storage	Raw water storage Treated water storage
System Administration	Administration and miscellaneous items Engineering Accounting In-lieu taxes

The cost functions developed herein are represented by a log-log relationship between the unit cost and the production rate. These relationships are presented as graphic plots from which the algebraic cost function employed in the preprocessing program is derived by determining two points on the graph and using the following basic equation:

$$C = a\,Q^{-b}$$

where

$$b = \frac{\log \frac{c_1}{c_2}}{\log \frac{q_2}{q_1}}$$

$$a = \frac{c_1}{q_1^{-b}}$$

C = unit cost (¢/1000 gal)
Q = flow rate (mgd)
c_1 = unit cost (¢/1000 gal), corresponding to point 1 on the curve
q_1 = flow rate (mgd), corresponding to point 1 on the curve
c_2 = unit cost (¢/1000 gal), corresponding to point 2 on the curve
q_2 = flow rate (mgd), corresponding to point 2 on the curve

In cases where the cost function does not plot as a straight line, the curve was closely approximated by two, or more, straight lines for ease in developing equations.

In a detailed study of a particular city or metropolitan area, it is necessary to identify specific quality parameters and derive accurate estimates for the associated treatment costs. For the purpose of this report, however, generalized cost functions were used when applicable. A more detailed discussion of the various cost elements and their cost functions is given in the following paragraphs.

Conventional Water Source Development

Water source development costs are highly dependent on the specific area or region being investigated; therefore, it is not feasible to formulate

generalized cost functions on this subject. Instead, the specific situation for any given city must be evaluated as a separate problem. For many cities, particularly for those with marginal water supplies, such studies have generally been performed to the required level of detail, requiring only minor updating for use in the present model.

Water Treatment

The cost functions developed for treatment of raw water supplies for municipal and other uses represent national averages and standard treatment sequences. The applicable cost functions are shown in Figure 4-1 for the following cases.

Surface Water Treatment, Conventional. This consists of chemical flocculation, sedimentation, rapid sand filtration, and chlorination. The unit cost function includes all capital charges, operation, and maintenance costs required for production of the water. Sludge disposal costs are also included.

Surface Water Treatment, With Softening. This is identical to the above but includes conventional lime-soda softening.

Groundwater Treatment, Conventional. This treatment consists of applying chlorine at a dosage of 4 mg/l.

Groundwater Treatment, With Demineralization. In this case, the cost function for electrodialysis (discussed under the paragraph on wastewater renovation) was used.

Additional Treatment for High-Grade Industrial Use. This treatment commonly consists of hot-lime softening followed by ion exhange; it was approximated for this study as the summation of the cost functions

for lime treatment and electrodialysis, described under the discussion on costs for wastewater renovation processes.

Seawater Distillation

To develop costs for seawater desalination, multistage flash distillation was selected for this study. The costs shown in Figure 4-2 are representative of plants operating with two different fuel costs — 20¢ and $40¢/10^6$ Btu. These costs were developed by Bechtel from information supplied by the OSW and include capital costs, plant staffing, and the groundrules noted in Table 4-2. No attempt was made to determine the benefits of possible electrical power generation coupled with a seawater distillation process.

Wastewater Renovation

The unit costs for wastewater renovation are presented in Figures 4-3 and 4-4 and are classified into the unit processes discussed in the ensuing paragraphs. These unit costs — adjusted to July 1969 prices — are derived from national surveys of treatment plants as reported by Smith and McMichael (Ref. 1), and Smith (Ref. 2). The unit process costs have been developed such that they are additive. For example, the cost for activated sludge treatment can be added directly to the cost for sand filtration to obtain a total cost for the facility.

Activated Sludge Treatment. The cost function shown in Figure 4-3 includes complete primary treatment, followed by conventionally designed activated sludge treatment consisting of aeration, final clarification, and sludge disposal.

Trickling Filter. Primary treatment, trickling filtration, clarification, and sludge disposal are included in the treatment costs shown in Figure 4-3.

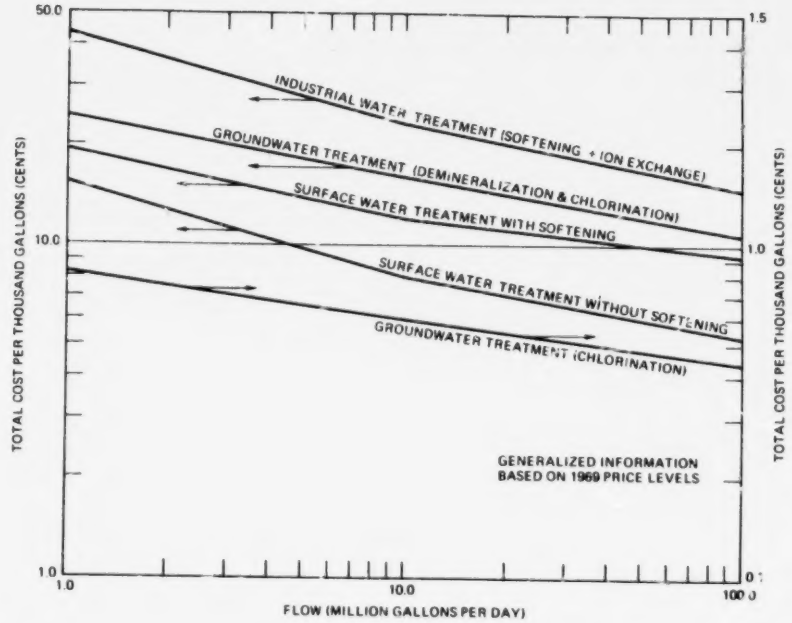


Figure 4-1. Water Treatment Costs

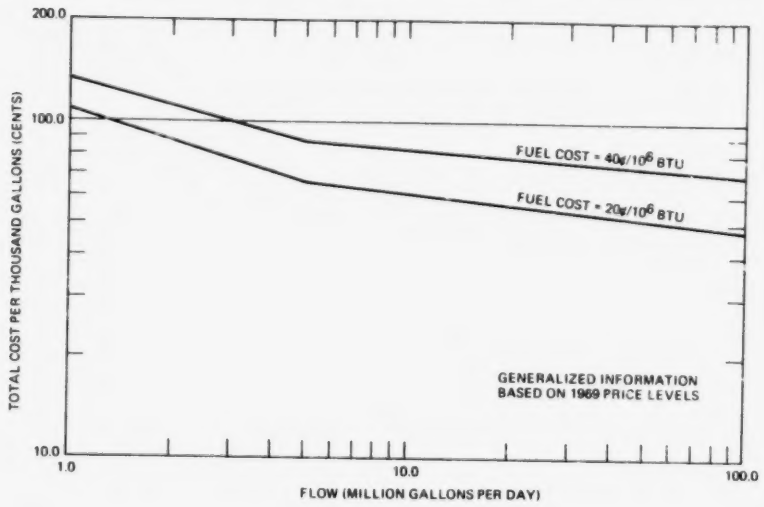


Figure 4-2. Seawater Distillation Costs

Secondary Effluent Chlorination. The cost for chlorination of either activated sludge or trickling filter effluent at a level of 8 mg/l is shown in Figure 4-3.

Lime Treatment and Ammonia Stripping. The cost function shown in Figure 4-4 includes costs of lime addition facilities, solids contact clarifiers, sludge concentrating equipment, recalcining furnaces, recarbonation basins, and ammonia stripping towers, complete with fans and lift pumps.

Dual-Media Filtration. Costs include gravity-flow dual-media filters with all associated piping and backwash systems required for filtration of secondary effluent. The cost function shown in Figure 4-4 is to be used in a treatment sequence preceded by an activated sludge or trickling filter plant.

Carbon Adsorption and Filtration. The costs shown in Figure 4-4 include carbon columns, initial carbon charge, associated backwash and regeneration, and ash disposal facilities required for treatment of secondary effluent.

Electrodialysis. The costs shown in Figure 4-4 are for a complete electrodialysis plant including membrane stacks, piping, electrical equipment, and buildings. In a sequence for treatment of wastewater, this element is intended for use after carbon adsorption and filtration. Brine disposal into the ocean was assumed to be at negligible costs.

Groundwater Injection. The characteristics of the local aquifers are the determining factors in the development of this cost function. For the purposes of this report, a unit cost of 5¢/1000 gal was used regardless of the flow rate. The cost was estimated from available data (Ref. 3), and included the costs for well drilling, casing, pumping, and operations and maintenance. Before injection, the water receives primary and secondary treatment, filtration, and chlorination.

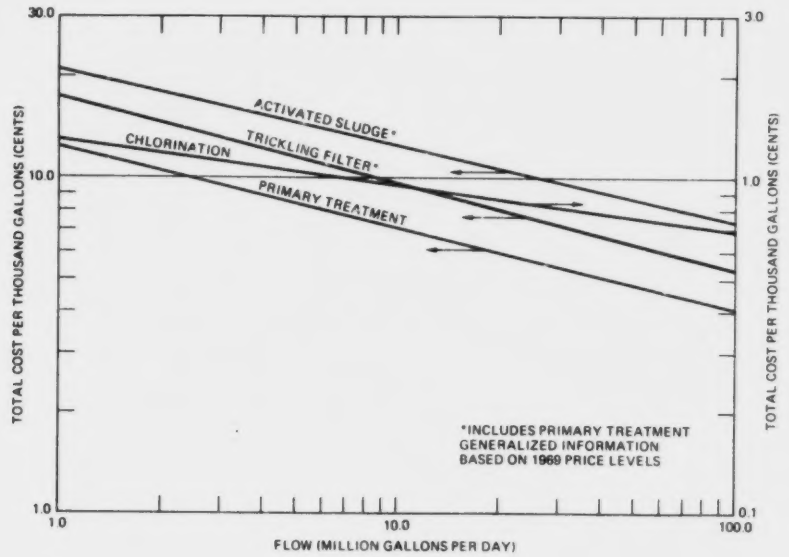


Figure 4-3. Costs of Activated Sludge, Trickling Filter, Effluent Chlorination, and Primary Treatment

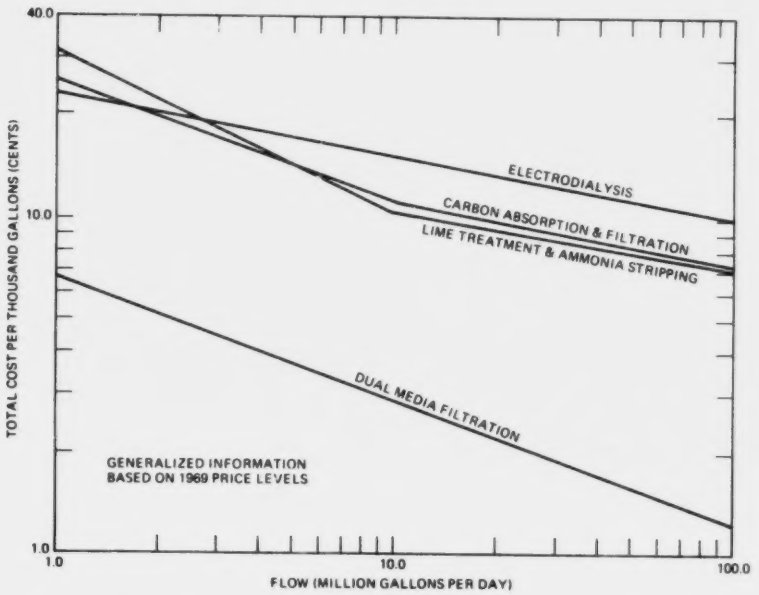


Figure 4-4. Costs of Lime Treatment and Ammonia Stripping, Dual Media Filtration, Carbon Adsorption and Filtration, and Electrodialysis

Wastewater Disposal

The following processes are among those that may be considered for wastewater treatment and ultimate disposal.

Primary Treatment Followed by Ocean Outfall. The general cost curve for primary treatment is given in Figure 4-3. For an ocean outfall, however, the cost is highly dependent on the bottom topography, prevailing winds, and currents in the receiving waters. A combined unit cost as a functional relation to the flow rate could be developed by an intensive study of the sites under consideration.

Activated Sludge Treatment. Where this treatment method is considered satisfactory for meeting receiving water requirements or necessary ahead of other treatment processes, the cost curve in Figure 4-3 can be used.

Activated Sludge Treatment Followed by Lime Treatment and Ammonia Stripping. The cost functions described for these processes under the renovation costs, and shown in Figures 4-3 and 4-4, can be used, if required.

Conveyance

Conveyance of water and wastewater involves transferring water from the source to the treatment plant and then, after treatment, to the distribution system. The water is taken from the distribution system, used, and returned to the wastewater collection system. The wastewater collection system, consisting of laterals and main sewers, transports the wastewater to trunk sewers that lead to the wastewater treatment plants. After physical, chemical, and/or biological treatment, the water may be reused, depending on the degree of treatment. In this case, it is conveyed to a demand point. Otherwise, it is treated and conveyed to an ultimate disposal site. The costs of these interrelated systems define what has been termed in this report as the conveyance cost elements.

Raw Water Conveyance. The costs associated with transporting water from a conventional source, such as an impoundment or a well field, to the treatment plant are highly site-sensitive; therefore, they are included in the source development costs discussed previously.

Treated Water Distribution System. The layout and sizing of the distribution system is not significantly different for the various alternatives considered in the mathematical model. The associated costs can, therefore, be included in the total system costs after the optimization procedure is completed.

Distilled and Renovated Water Conveyance. These costs include the costs of conveying the product water from the plant to a demand.

The cost functions were based on cents per thousand gallons conveyed per mile of pipe and were derived from data provided by Harmeson (Ref. 4), Smith (Ref. 2), and available Bechtel information. The cost curves for conveyance of water are shown in Figure 4-5 for three types of conveyance routes.

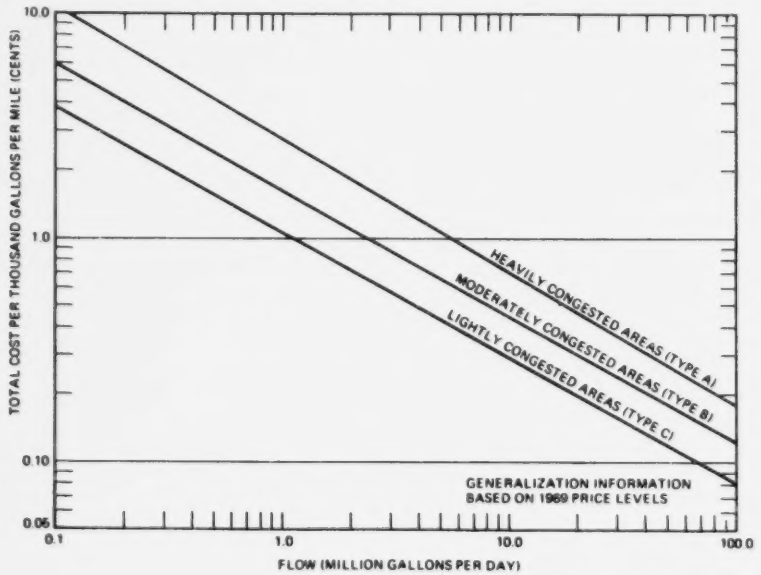


Figure 4-5. Treated Water Conveyance Costs

It was assumed that the headloss in the conveyance system would be 1.5 ft/1000 ft, and that the Hazen-Williams coefficient, C, would equal 100. All costs include an annual amortization charge of 5.4 percent of the capital investment. An annual charge of 0.25 percent on the capital investment was included for operation and maintenance of the system.

The costs for pumping stations and power requirements are included in the following cost function. This cost was added to the conveyance cost in the model.

$$Cp = \left[7.92\ (\text{Dist. A} + \text{Dist. B} + \text{Dist. C}) + \text{Elev.}\right] \left[0.00565 + 0.0283Q^{-0.223}\right]$$

where

Cp	=	unit cost (¢/1000 gal)
Dist. A	=	length of pipe through Type A areas (miles)
Dist. B	=	length of pipe through Type B areas (miles)
Dist. C	=	length of pipe through Type C areas (miles)
Elev.	=	static pumping head (feet)
Q	=	flow rate (mgd)

Wastewater Collection System. Similar considerations given to the water distribution systems can also be given to the wastewater collection systems. The associated costs can be included in the total system costs after the optimization process is completed.

Wastewater Conveyance (Trunk Sewers). The cost associated with trunk sewers was determined by using the same methodology indicated under the discussion on distilled and renovated water conveyance. The cost functions discussed there and shown in Figure 4-5 were also used for the sewers, after being multiplied by a factor of 0.75 to account for the slightly lower costs experienced, in general, for sewer construction and operation compared to water lines.

Storage

Provisions for storage must be made for raw and treated water in a large supply system to meet fluctuating supplies and demands. In general, storage facilities are very site-sensitive and, therefore, require in-depth investigations. The storage costs in this study are discussed below.

Raw Water. This item, which pertains only to the conventional surface water sources, has been included in the source development costs.

Treated Water Storage. Within a municipal distribution system, storage must be provided for peak demands and for fire requirements. The costs associated with such facilities have been included in the treated water distribution system costs for those demands supplied by conventional water sources.

Because of the hourly variation in the demands and the wastewater available for renovation, provisions were made in the model to account for the costs of adequate storage facilities for this type of supply. In this study, it was assumed that a 6-hour detention time based on the mean flow would provide adequate storage to compensate for these variations. For the cost developed in this study, it was assumed that ground-level storage tanks would be used.

The estimated costs for storage facilities in terms of cents per thousand gallons of flow are shown in Figure 4-6.

System Administration

The cost elements related to this item do not significantly affect the selection of an optimal system; therefore, they can be added after the optimization process has been completed, in order to determine the total annual cost of a water supply/wastewater disposal system.

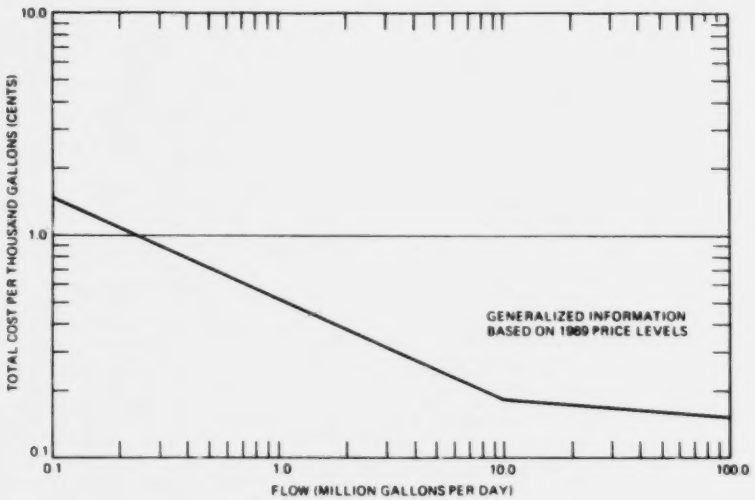


Figure 4-6. Storage Costs

A review of the annual financial reports of the utility divisions from several cities indicated that these costs represent a significant fraction of the total annual costs. The items related to these costs are discussed in the following paragraphs.

Administration and Miscellaneous Items. Included in these items are such costs as office facilities, retirement funds, compensation insurance, damage claims, general expenses, and uncollectable accounts.

Engineering. This cost item is related to the day-to-day engineering requirements and does not include the engineering and construction management costs associated with building new facilities.

Accounting. Included in this item are the cost of general accounting, preparation of monthly statements, collecting accounts, and paying expenses.

In-Lieu and Social Security Taxes. Often a portion of the expenses for a water and wastewater system is for in-lieu franchise or property taxes. Social Security taxes are also an expense item.

Total System Costs. The total annual cost related to the overall system must be determined to evaluate the importance of possible savings related to a particular alternative of supplying the demands. An interesting concept is the evaluation of the percent increase in costs related to the production of higher-quality water. To develop the correct perspective of these costs, such comparisons require knowledge of the total system expenditures. They should not be made on the basis of the costs of individual unit processes taken out of the context of the overall system.

Section 5

TESTING OF NETWORK MODEL — WATER PLANNING CASE EXAMPLE

Section 5

TESTING OF NETWORK MODEL – WATER PLANNING CASE EXAMPLE

The network model and cost information described in previous sections of this report were used to solve a water planning case for a hypothetical community. The statement of the problem, the application of the model, and a discussion of the solution are contained in this section. The example is primarily intended for evaluation of the model performance and does not reflect all factors that would be considered in an in-depth study of a metropolitan region. To facilitate comparison, the figures and tables cited in the following pages are grouped at the end of this section.

PROBLEM DESCRIPTION

The primary elements of the problem selected are illustrated in Figure 5-1. For this problem there are two municipal water demands (M1 and M2), one industrial cooling water demand (I1), one industrial process water demand (I2), and one agricultural irrigation demand (A1). Major groundrules for the problem are specified in Table 5-1.

The water supplies considered for this example consist of two conventional surface water treatment plants (S1 and S2), one seawater distillation plant (D1), and two wastewater renovation plants (R1 and R2), all shown in Figure 5-1. The water demands and water availabilities assumed for each supply are also shown in Figure 5-1, as well as the conveyance distances and pumping head requirements between the various

supplies and demands. As can be seen, each type of demand can be supplied from two or more alternative supplies. The fundamental problem to be solved is, therefore, to select the least-cost alternatives to supply the indicated demands.

APPROACH

A preliminary analysis of the problem indicated that blending of distilled seawater with the conventional water sources would be necessary to meet the 500-mg/l-TDS requirement for municipal use. The basic approach for solving a problem of this type, as outlined in Section 3, was used. The network was initially structured from the basic data and then a solution obtained in which blending was not considered. For this solution, the conventional water and distilled seawater required at each municipal demand was calculated and flow constraints placed on the arcs representing the seawater distillation process such that the required blend would be forced in the final solution. The least-cost solution for the problem with the necessary constraints was then generated with the network model.

NETWORK STRUCTURE

The schematic diagram in Figure 5-1 represents a physical concept of the region defined in terms of demands, sources, and conveyance routes. From this diagram, a network structure consisting of arcs and nodes was established, as shown in Figure 5-2, to represent each process or group of processes required between the various sources and demands.

As pointed out in Section 3, all sources originate from a common node, S, and all demands terminate at a common node, T. The S and T nodes have been shown separately in Figure 5-2 for each source and demand, respectively, for clarity. These nodes are connected by a return arc as indicated. The various functions of each arc will be discussed in greater detail later in this section of the report.

INPUT DATA

A separate computer data card was prepared for each arc in the network containing information related to (1) the supply (initial) and demand (terminal) node designations, (2) constraints on the allowable flows, (3) the assumed flow initially used in the preprocessing program to calculate the unit cost, and (4) locational aspects of the activity represented by each arc. The data card was also used to identify or flag the cost function(s) in the preprocessing program that were applicable to the specific activity represented by the arc. The input data format shown in Table 3-1 was followed. After the input data were prepared, the problem was analyzed using the treatment requirements shown in Figure 3-4 and applicable cost data from Section 4, in conjuntion with the network model.

PROBLEM SOLUTIONS

Two solutions for the hypothetical network problem were generated using the network model. The first solution, shown in Figure 5-3, does not take into account the quality constraints given in Table 5-1. In this first solution, the municipal demand M1 was supplied by the conventional water source S1 and the renovated wastewater source R1. Municipal demand M2 was supplied by the conventional water source S2 and the renovated wastewater source R2. The industrial cooling water demand I1 was supplied by renovated wastewater from source R1, and the industrial process water demand I2 was supplied by the distilled seawater source D1 which does not require lime-softening and ion exchange treatment. Agricultural irrigation demand A1 was also supplied by renovated wastewater from source R2.

The results of this first solution indicated that in this case the construction of two water treatment plants and two wastewater renovation plants was preferred to one large plant of each type. Thus, the economics of scale associated with larger facilities were offset in this example by the decrease in conveyance costs associated with the smaller plants. The

indicated use of renovated wastewater for the municipal demands will require further research and approval by public health officials. However, based on the assumptions and cost data used in the example problem, the potential feasibility of using renovated wastewater for municipal demands appeared as a possibility.

The second solution obtained is shown in Figure 5-4. In this case, use was made of the total dissolved solids (TDS) requirements shown in Table 2. As shown in Figure 5-4, the results of this analysis were essentially the same as those obtained in the first solution (Figure 5-3) except that distilled seawater from source D1 was used to improve the municipal demand quality by reducing the TDS to 500 ppm and renovated wastewater was not used for the municipal demands.

Although the example problem and solutions presented are relatively simple compared to a large municipal area, other preliminary investigations have been conducted using the network model on three large cities. The results from these investigations, as well as the example problem presented, indicate that the model can be used as a powerful tool in planning complex water supply/wastewater disposal systems.

PRINTOUT ANALYSIS

Tables 5-2 and 5-3 are computer printout sheets for the water planning problem. Table 5-2 summarizes the basic input data and Table 5-3 presents the optimum solution for the given demands and constraints. The printout sheet terminology is defined with each table.

Together with a listing of the basic data, Table 5-2 lists the unit costs computed by the preprocessing program for each process specified. A total unit cost for each arc is also given. The assumed flows shown were utilized with the cost-flow functions of Section 4 to compute the

unit costs at the start of the computer run. These flows are not the initially assumed flows but are the flows that have been replaced by the model during the iterative procedures as discussed in Section 3.

Computer printout sheets outlining the status of the network at the optimal solution are presented in Table 5-3. For each arc the defined upper and lower flow constraints, together with the computed unit cost and the arc flow at optimum conditions are shown. Although not part of the actual printout, the processes represented by each arc are listed for reference. It should be noted that these processes may also be found in Table 5-2 as entries under the unit cost items.

The total cost shown in Table 5-3 is a summation of the products of the arc flows and their unit costs at the optimum condition, converted to an annual basis. This total cost does not include the cost of system administration, taxes, and collection and distribution facilities (except the conveyance requirements shown in the problem description). These items must be established for each municipality investigated.

Shown in Appendix D of this report is a series of hand calculations which verify the calculations obtained at the optimum solution produced by the computer.

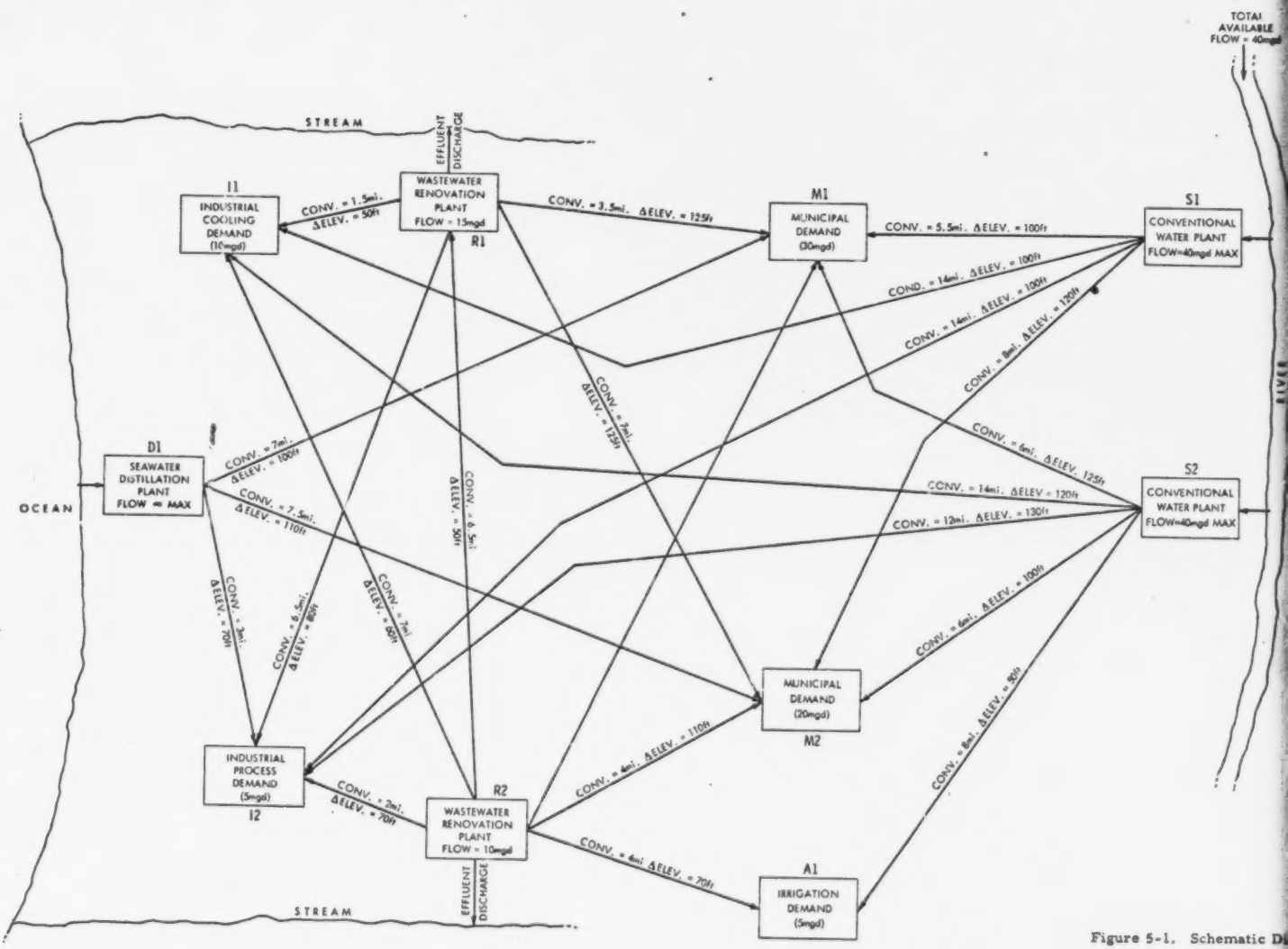

TOTAL AVAILABLE FLOW = 40mgd
STREAM
EFFLUENT DISCHARGE
I1
INDUSTRIAL COOLING DEMAND (10mgd)
CONV. = 1.5mi. ΔELEV. = 50ft
WASTEWATER RENOVATION PLANT FLOW = 15mgd
R1
CONV. = 3.5mi. ΔELEV. = 125ft
M1
MUNICIPAL DEMAND (30mgd)
CONV. = 5.5mi. ΔELEV. = 100ft
S1
CONVENTIONAL WATER PLANT FLOW=40mgd MAX
COND. = 14mi. ΔELEV. = 100ft
CONV. = 14mi. ΔELEV. = 100ft
CONV. = 8mi. ΔELEV. = 125ft
CONV. = 7mi. ΔELEV. = 175ft
CONV. = 6mi. ΔELEV. 125ft
D1
SEAWATER DISTILLATION PLANT FLOW = MAX
CONV. = 7mi. ΔELEV. = 100ft
CONV. = 7.5mi. ΔELEV. = 110ft
S2
CONVENTIONAL WATER PLANT FLOW=40mgd MAX
CONV. = 14mi. ΔELEV. = 120ft
CONV. = 12mi. ΔELEV. = 130ft
OCEAN
CONV. = 9.5mi. ΔELEV. = 90ft
CONV. = 3mi. ΔELEV. = 70ft
CONV. = 8.5mi. ΔELEV. = 80ft
CONV. = 2mi. ΔELEV. = 60ft
CONV. = 6mi. ΔELEV. = 100ft
MUNICIPAL DEMAND (20mgd)
M2
INDUSTRIAL PROCESS DEMAND (5mgd)
I2
CONV. = 2mi. ΔELEV. = 70ft
R2
WASTEWATER RENOVATION PLANT FLOW = 10mgd
CONV. = 4mi. ΔELEV. = 110ft
CONV. = 6mi. ΔELEV. = 90ft
CONV. = 4mi. ΔELEV. = 70ft
A1
IRRIGATION DEMAND (5mgd)
EFFLUENT DISCHARGE
STREAM

Figure 5-1. Schematic Di
Water Planni

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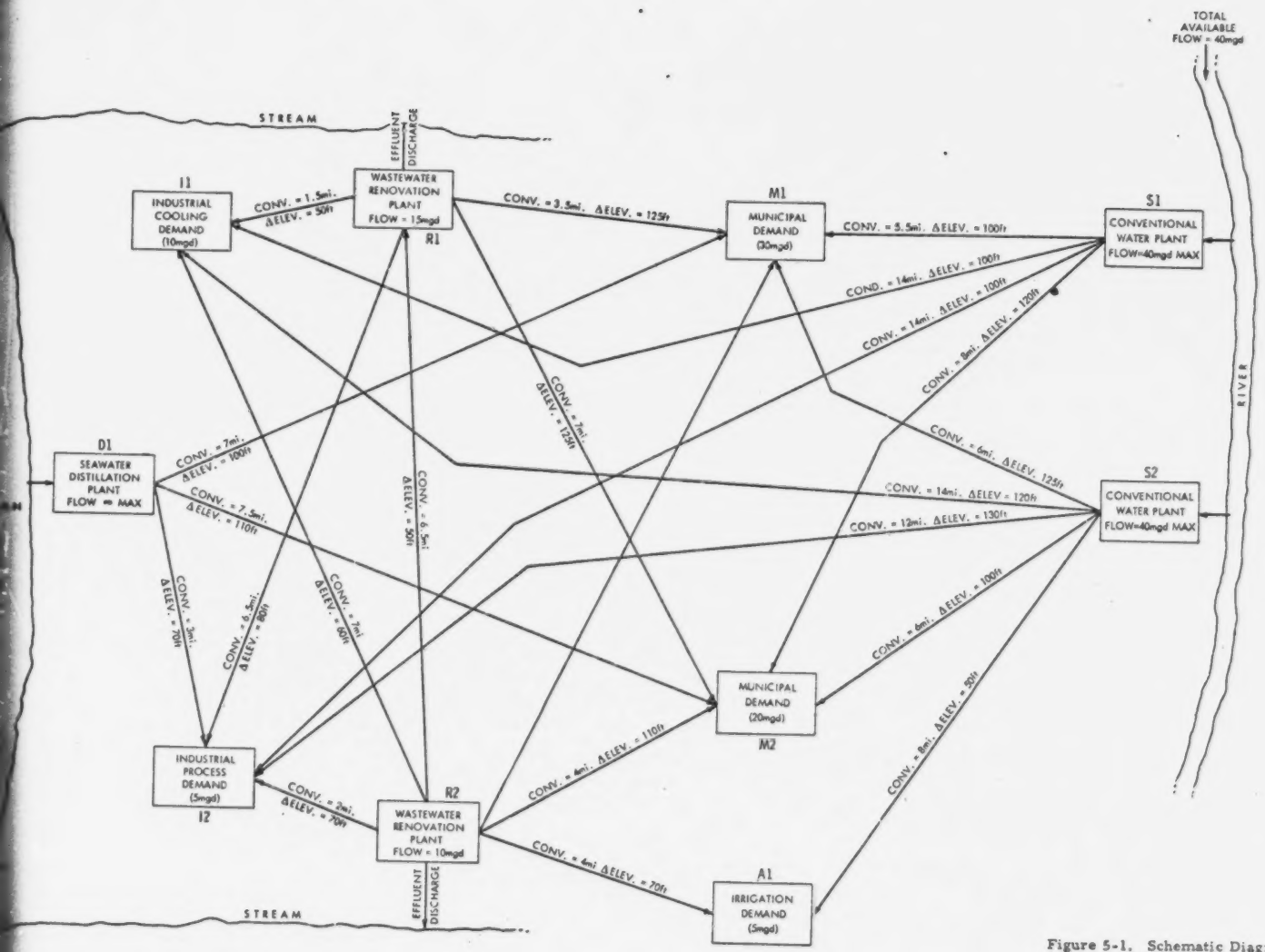
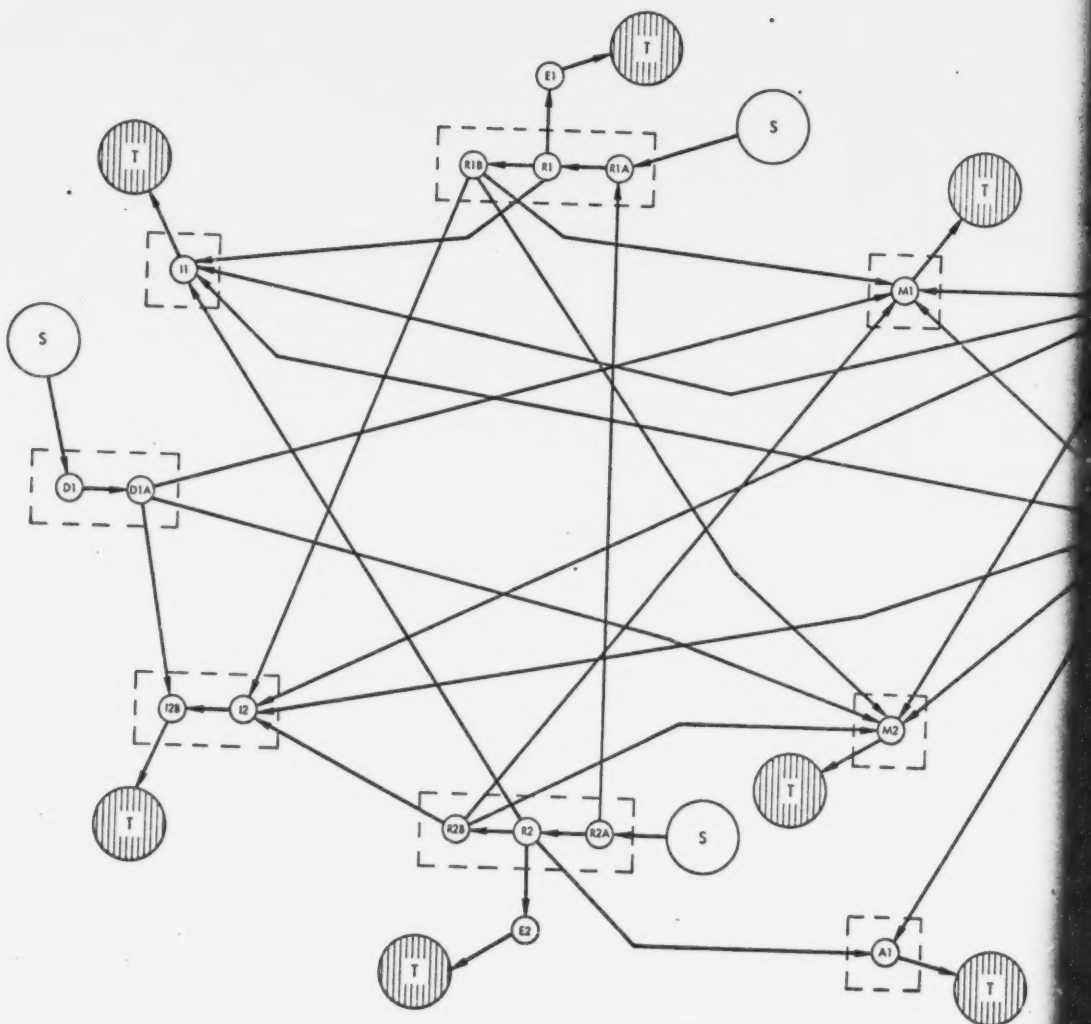

TOTAL AVAILABLE FLOW = 40mgd
STREAM
EFFLUENT DISCHARGE
I1
INDUSTRIAL COOLING DEMAND (10mgd)
CONV. = 1.5mi. ΔELEV. = 50ft
WASTEWATER RENOVATION PLANT FLOW = 15mgd
R1
CONV. = 3.5mi. ΔELEV. = 125ft
M1
MUNICIPAL DEMAND (30mgd)
CONV. = 5.5mi. ΔELEV. = 100ft
S1
CONVENTIONAL WATER PLANT FLOW=40mgd MAX
COND. = 14mi. ΔELEV. = 100ft
CONV. = 14mi. ΔELEV. = 100ft
CONV. = 8mi. ΔELEV. = 120ft
CONV. = 7mi. ΔELEV. = 125ft
RIVER
D1
SEAWATER DISTILLATION PLANT FLOW = MAX
CONV. = 7mi. ΔELEV. = 100ft
CONV. = 7.5mi. ΔELEV. = 110ft
CONV. = 6mi. ΔELEV. 125ft
CONV. = 14mi. ΔELEV = 120ft
S2
CONVENTIONAL WATER PLANT FLOW=40mgd MAX
CONV. = 12mi. ΔELEV. = 130ft
CONV. = 3mi. ΔELEV. = 70ft
CONV. = 8.5mi. ΔELEV. = 80ft
CONV. = 7mi. ΔELEV. = 60ft
CONV. = 6.5mi. ΔELEV. = 50ft
CONV. = 6mi. ΔELEV. = 100ft
MUNICIPAL DEMAND (20mgd)
M2
INDUSTRIAL PROCESS DEMAND (5mgd)
I2
CONV. = 2mi. ΔELEV. = 70ft
R2
WASTEWATER RENOVATION PLANT FLOW = 10mgd
CONV. = 4mi. ΔELEV. = 110ft
CONV. = 8mi. ΔELEV. = 30ft
CONV. = 4mi ΔELEV. = 70ft
A1
IRRIGATION DEMAND (5mgd)
EFFLUENT DISCHARGE
STREAM

Figure 5-1. Schematic Diagram for Water Planning

B

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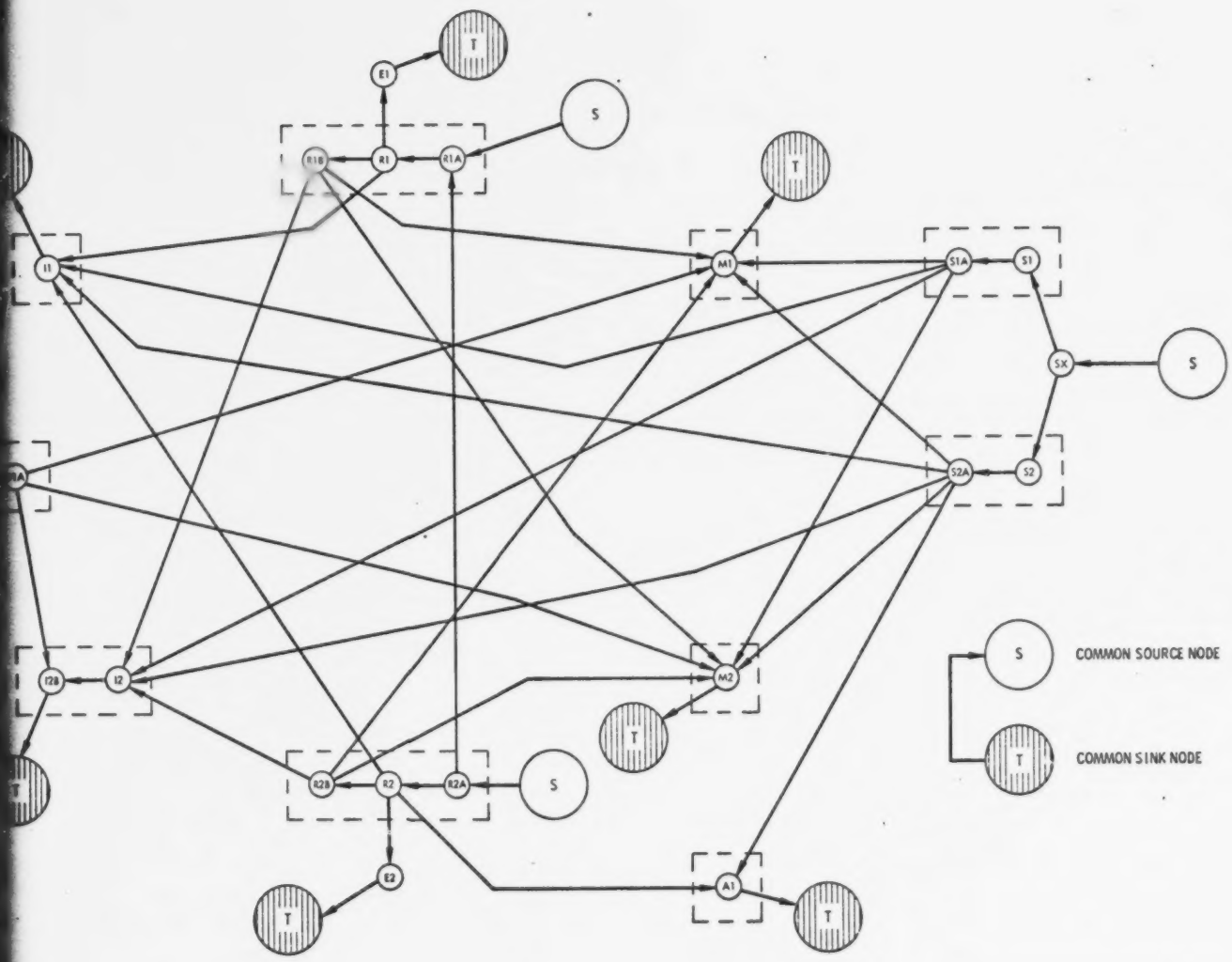


Figure 5-2. Network for Water Planning Case

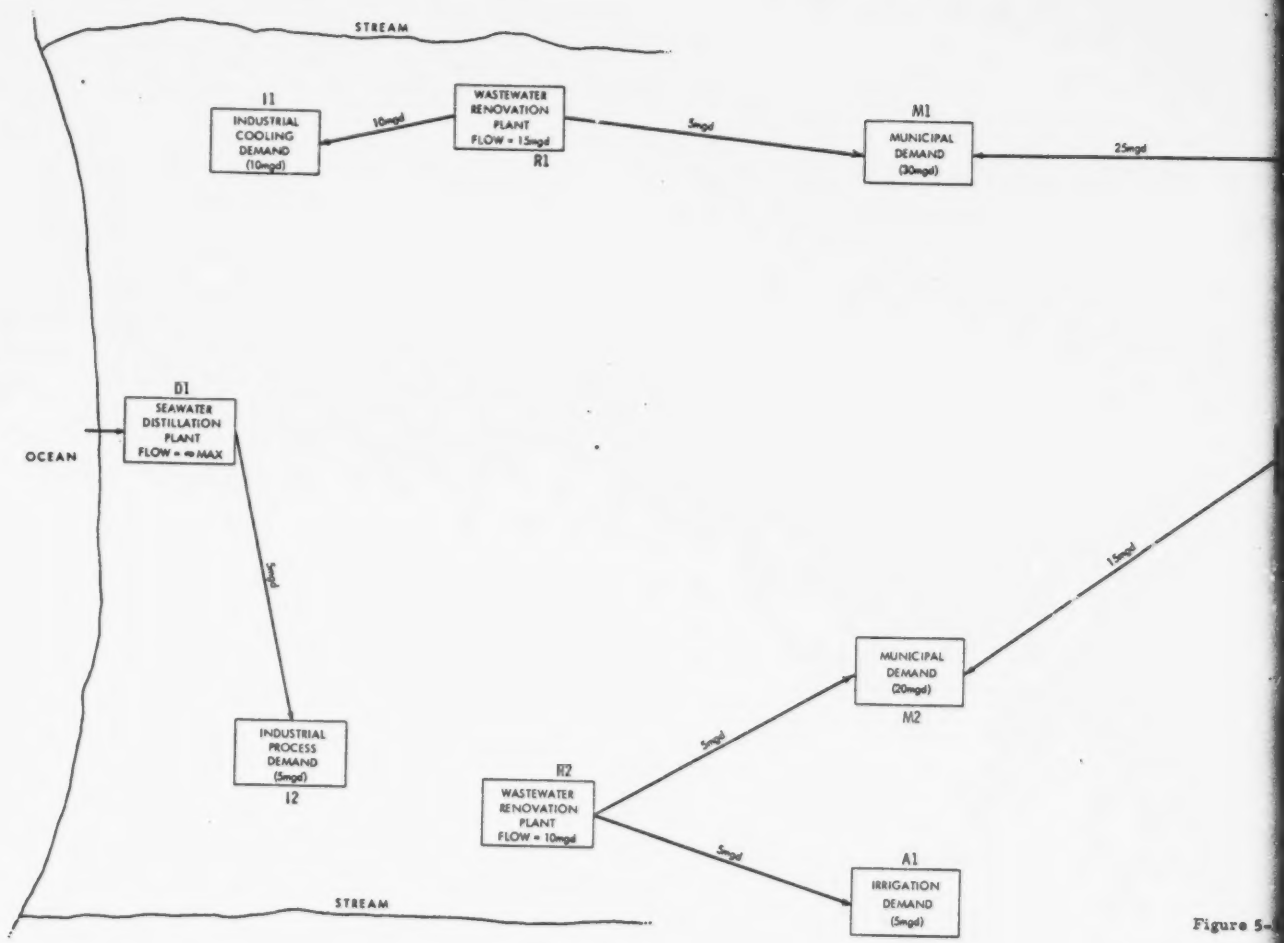


Figure 5-

A

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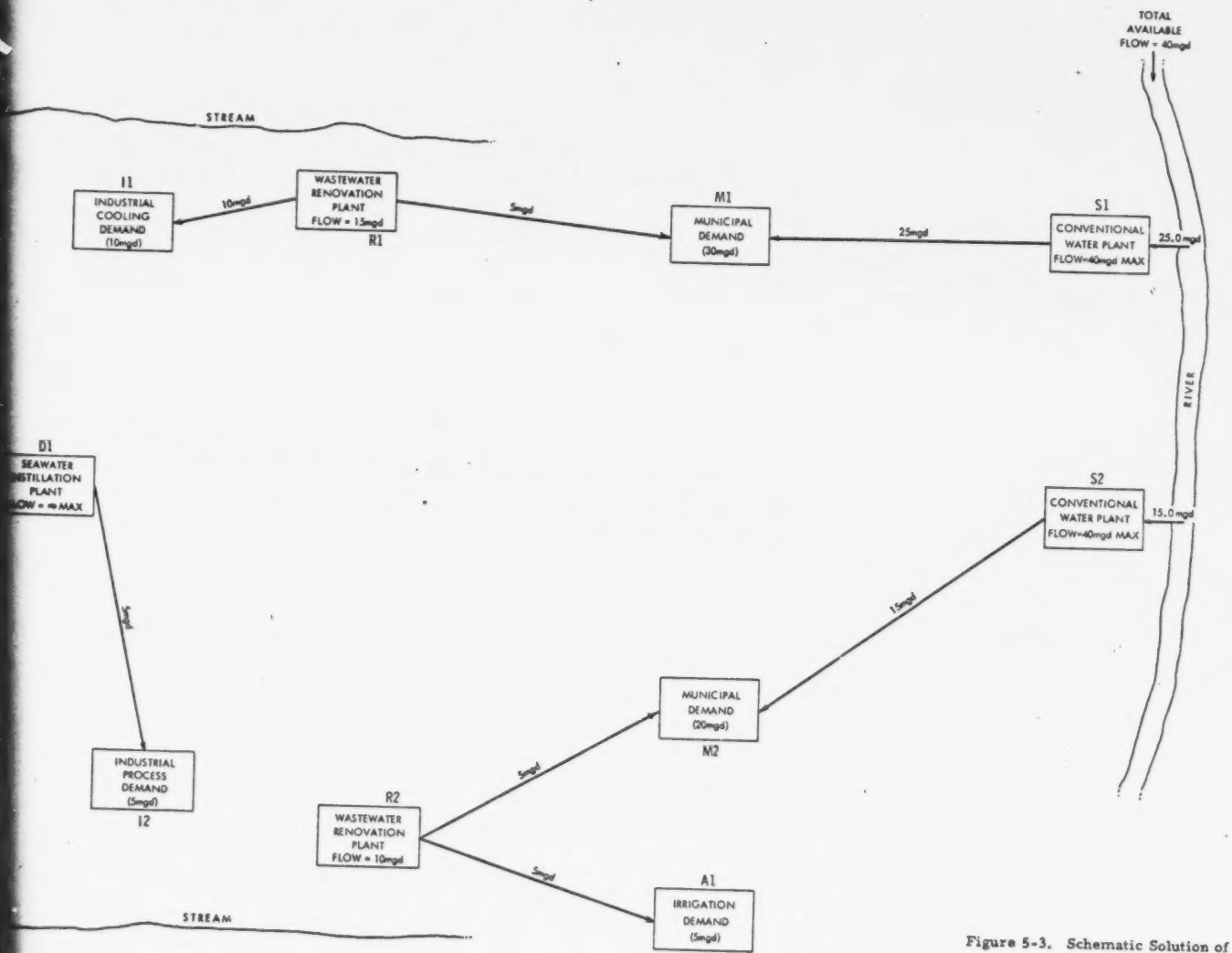


Figure 5-3. Schematic Solution of Water Planning Case – With Blending

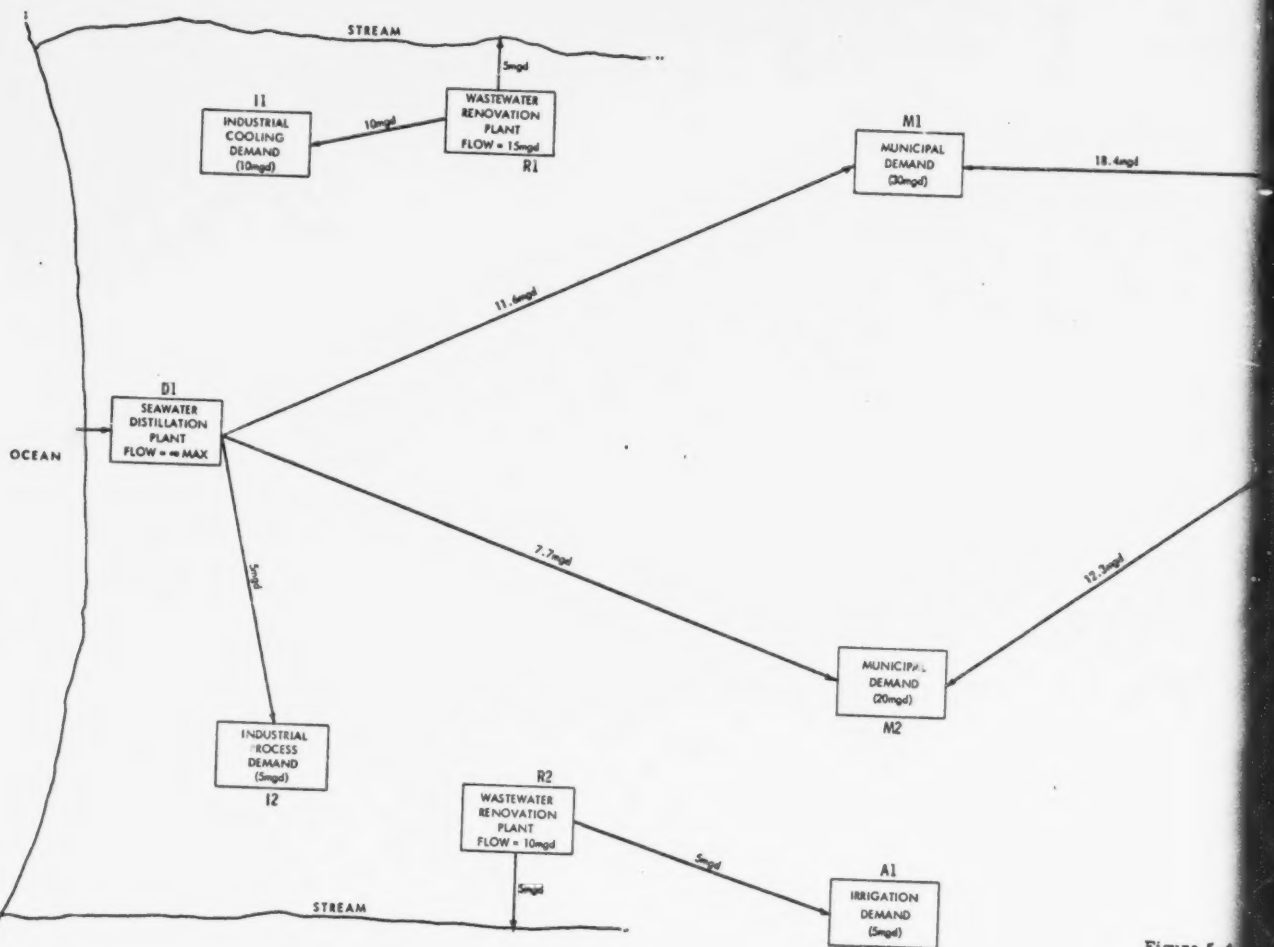


Figure 5-4

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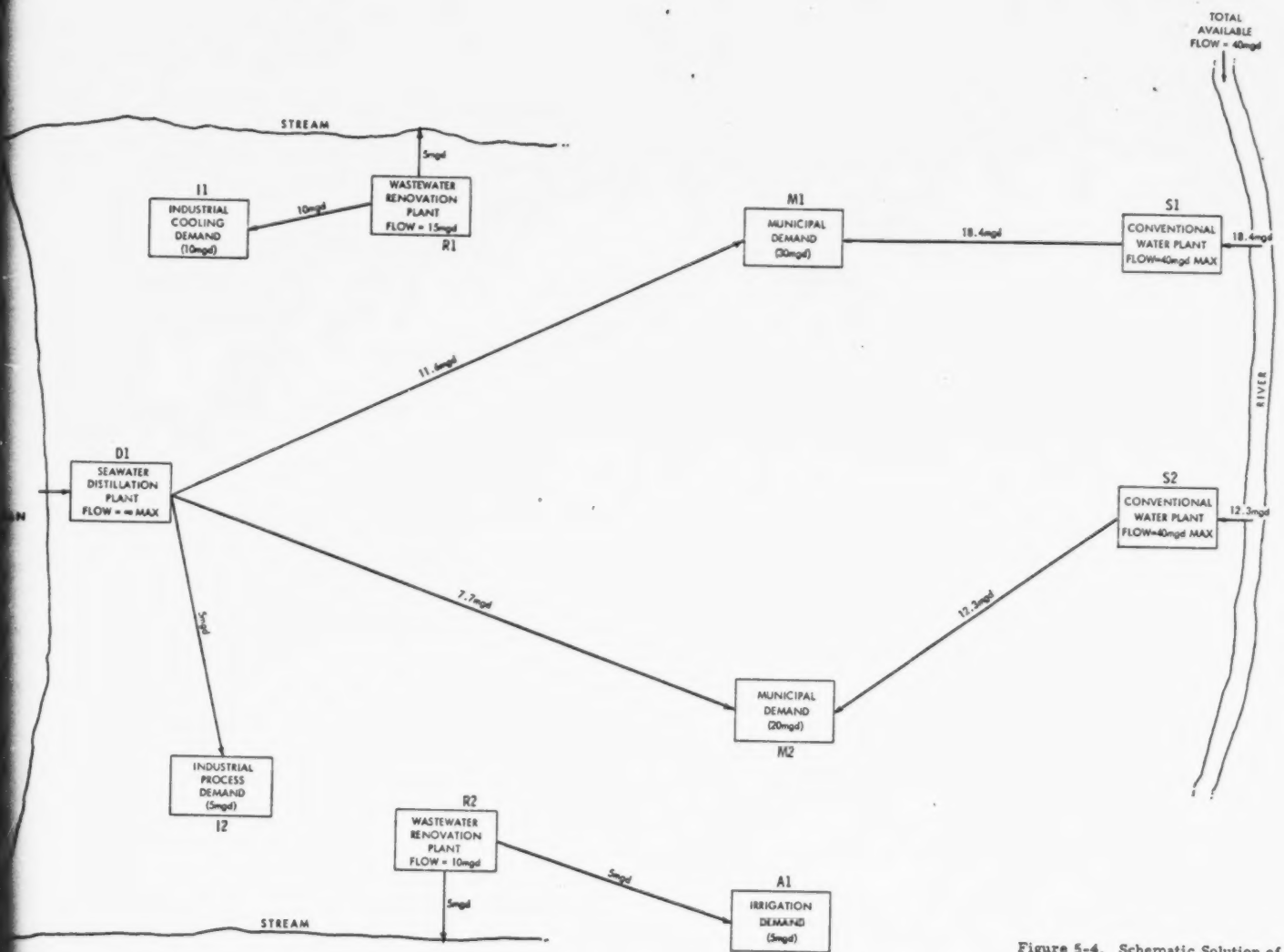


Figure 5-4. Schematic Solution of Water Planning Case — Without Blending

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Table 5-1

MAJOR GROUNDRULES FOR WATER PLANNING CASE

- Conventional water sources were assumed to have 800 mg/l TDS. Costs for the available conventional water sources were taken at 20¢/1000 gallons delivered to the water plants.
- The maximum dissolved solids contents for the water uses were assumed to be:

	TDS (mg/l)
Municipal	500
Industrial process	100
Industrial cooling	1,200
Irrigational	1,200

- Untreated wastewater was assumed to have 1200 mg/l TDS, and demineralized renovated wastewater was assumed to have 500 mg/l TDS.
- Distilled seawater with 25 mg/l TDS was used for blending to achieve quality specifications when required.
- Primary followed by activated sludge treatment was assumed to meet receiving water requirements.

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Table 5-2

ECONOMICS OF COMBINED SEAWATER DISTILLATION AND WASTEWATER RENOVATION SYSTEMS NETWORK MODEL – BASIC INPUT DATA

Item	Definition of Terms
Init. Node	Initial arc node from which flow occurs
Term. Node	Terminal arc node at which flow arrives
Max Flow (mgd)	Maximum flow in million gallons per day permitted in the arc
Min Flow (mgd)	Minimum flow permitted in the arc
Ass. Flow (mgd)	Initially assumed flow in the arc for which unit costs are developed
Unit Cost (c/kg)	Total unit cost in cents per 1000 gallons for all processes represented by the arc
Distance (miles)	Length of conveyance shown in miles
A, B, C	Various types of conveyance routes
Elev. (ft)	Static pumping head for the arc
Unit Costs (c/kg) for Individual Cost Items	Unit costs in cents per 1000 gallons for each process represented by the arc as defined by the cost functions derived in Section 4
CSUPM	Cost of municipal source development and raw water conveyance
CSUPA	Cost of agricultural source development and raw water conveyance
CSWTR	Cost of surface water treatment without softening
CP	Cost of primary treatment
CAS	Cost of activated sludge treatment
CF	Cost of dual media filtration
CPNC	Cost of phosphorus and nitrogen removal, and carbon adsorption
CED	Cost of electrodialysis
CSEW	Cost of wastewater conveyance
CSD	Cost of seawater distillation
CCON	Cost of treated water conveyance
CIND	Cost of industrial water treatment using lime softening and ion exchange
CSTOR	Cost of treated water storage based on a fixed detention time of the average flow (6 hr)

ECONOMICS OF COMBINED SEAWATER DISTILLATION
AND WASTEWATER RENOVATION SYSTEMS
NETWORK MODEL--BASIC INPUT DATA

INIT. NODE	TERM. NODE	MAX FLOW (MGD)	MIN FLOW (MGD)	ASS. FLOW (MGD)	UNIT COST (C/KG)	DISTANCE (MILES) A	B	C	ELEV. (FT)	UNIT COSTS (C/KG) FOR INDIVIDUAL COST ITEMS (SAN DIEGO) CSUPR	CSUPA	CSWTR	CP	CAS	CF	CPNC	CRD	CSEW	CSD	CCON	CIND	CSTOR
S1	S1A	999.9		18.4	27.35					20.0	7.2											0.2
S1A	M1	999.9		18.4	4.61		5.5		100.										4.6			
S1A	I1	999.9		0.1	94.42		14.0		100.										94.4			
S1A	I2	999.9		0.1	94.42		14.0		100.										94.4			
S1A	M2	999.9		0.1	57.25		8.0		120.										57.2			
S2	S2A	999.9		12.3	27.89					20.0	7.7											0.2
S2A	M1	999.9		0.1	44.77		6.0		125.										44.8			
S2A	M2	999.9		12.3	5.51		6.0		100.										5.5			
S2A	I1	999.9		0.1	95.47		14.0		120.										95.5			
S2A	I2	999.9		0.1	83.25		12.0		130.										83.3			
S2A	A1	999.9		0.1	53.58		8.0		50.										53.6			
D1	D1A	999.9		24.3	55.48													55.5				
D1A	M1	11.6	11.6	11.6	6.19		7.0		100.										6.2			
D1A	M2	7.7	7.7	7.7	7.72		7.5		110.										7.7			
D1A	I2B	999.9		5.0	4.27		3.0		70.										4.3			
R1A	R1	999.9		15.0	11.35								11.3									
R1	I1	999.9		10.0	5.05		1.5		50.					2.8					2.0		0.2	
R1	E1	999.9		5.0																		
R1	R1B	999.9		0.5	109.44										76.8	31.9					0.7	
R1B	M1	999.9		0.1	28.65		3.5		125.										28.6			
R1B	M2	999.9		0.1	51.14		7.0		125.										51.1			
R1B	I2	999.9		0.1	45.60		5.5		80.										45.6			
R2A	R2	999.9		10.0	12.44								12.4									
R2A	R1A	999.9		0.1	34.35		6.5		50.								34.3					
R2	I1	999.9		0.5	30.36		7.0		60.					8.7					20.7		0.7	
R2	E2	999.9		5.0																		
R2	A1	999.9		5.0	5.35		4.0		70.										5.1		0.2	
R2	R2B	999.9		0.5	109.44										76.8	31.9					0.7	
R2B	M1	999.9		0.1	54.59		7.5		130.										54.6			
R2B	M2	999.9		0.1	31.25		4.0		110.										31.2			
R2B	I2	999.9		0.1	16.41		2.0		70.										16.4			
I2	I2B	999.9		0.5	52.25															52.2		
S	SX	40.0		30.7																		
S	R1A	15.0	15.0	15.0																		
S	R2A	10.0	10.0	10.0																		
S	D1	999.9		24.3																		
SX	S1	40.0		18.4																		
SX	S2	40.0		12.3																		
E1	T	999.9		5.0																		
E2	T	999.9		5.0																		
M1	T	999.9	30.0	30.0																		
M2	T	999.9	20.0	20.0																		
I1	T	999.9	10.0	10.0																		
I2B	T	999.9	5.0	5.0																		
A1	T	999.9	5.0	5.0																		
T	S	999.9		80.0																		

Table 5-3

OUT-OF-KILTER NETWORK FLOW
STATUS OF NETWORK AT OPTIMAL SOLUTION

Item	Definition of Terms
Starting Node	Initial arc node from which flow occurs
Node No.	Arbitrarily assigned number for each node
Ending Node	Terminal arc node at which flow arrives
Cost	Total unit cost in cents per 1000 gallons of all processes represented by the arc
Upper Bound	Upper limit of flow which can occur in the arc. Established as 999.90 if no other requirements govern
Lower Bound	Lower limit of flow which can occur in the arc. Established as equal to Upper Bound if flow in arc is fixed
Flow in Arc	Flow in the arc at the optimum solution which satisfies all constraints and demands
Processes Represented by the Arc	Listing of flow processes from Table 3-1 that are represented by the arc (not shown in the original printout sheet)

STATUS OF NETWORK AT OPTIMAL SOLUTION

STARTING NODE	NODE NO.	ENDING NODE	NODE NO.	COST	UPPER BOUND	LOWER BOUND	FLOW IN ARC	PROCESSES REPRESENTED BY THE ARC
S1	1	S1A	2	27.34	999.90	0.	18.40	Source Development - Treatment - Storage
S1A	2	M1	18	4.61	999.90	0.	8.40	Treated Water Conveyance
S1A	2	I1	20	94.41	999.90	0.	0.	" " "
S1A	2	I4	13	94.41	999.90	0.	0.	" " "
S1A	2	M4	19	97.24	999.90	0.	0.	" " "
S2	3	S2A	4	27.88	999.90	0.	12.30	Source Development - Treatment - Storage
S2A	4	M1	18	44.77	999.90	0.	0.	Treated Water Conveyance
S2A	4	M2	19	5.51	999.90	0.	12.30	" " "
S2A	4	I1	20	95.46	999.90	0.	0.	" " "
S2A	4	I4	13	83.25	999.90	0.	0.	" " "
S2A	4	A1	22	53.57	999.90	0.	0.	" " "
D1	5	D1A	6	55.48	999.90	0.	24.30	Water Distillation
D1A	6	M1	18	0.19	11.60	11.60	11.60	Treated Water Conveyance
D1A	6	M4	19	7.71	7.70	7.70	7.70	" " "
D1A	6	I2B	21	4.27	999.90	0.	5.00	" " "
R1A	7	R1	8	11.34	999.90	0.	15.00	Activated Sludge
R1	8	I1	20	5.05	999.90	0	10.00	Filtration - Treated Water Conveyance - Storage
R1	8	E1	16	0.	999.90	0.	5.00	Disposal
M1	8	M1B	9	109.43	999.90	0.	0.	Phos. & Nit. Removal - Electrodialysis - Storage
R1B	9	M1	18	28.84	999.90	0.	0.	Treated Water Conveyance
R1B	9	M4	19	51.14	999.90	0.	0.	" " "
R1B	9	I4	13	45.59	999.90	0.	0.	" " "
R2A	10	R2	11	12.43	999.90	0.	10.00	Activated Sludge
R2A	10	M1A	7	34.34	999.90	0.	0.	Sewage Conveyance
R2	11	I1	20	89.05	999.90	0.	0.	Filtration - Treated Water Conveyance - Storage
R2	11	E4	17	0.	999.90	0.	5.00	Disposal
R2	11	A1	22	5.35	999.90	0.	5.00	Treated Water Conveyance - Storage
M2	11	M2B	12	109.43	999.90	0.	0.	Nit. & Phos. Removal - Electrodialysis - Storage
R2B	12	M1	18	54.58	999.90	0.	0.	Treated Water Conveyance
R2B	12	M4	19	31.24	999.90	0.	0.	" " "
R2B	12	I4	13	16.40	999.90	0.	0.	" " "
I2	13	I2B	21	52.24	999.90	0.	0.	Industrial Water Treatment - Ion Exchange
S	14	SX	15	0.	40.00	0.	30.70	Model Constraints
S	14	M1A	7	0.	15.00	15.00	15.00	" "
S	14	M2A	10	0.	10.00	10.00	10.00	" "
S	14	D1	5	0.	999.90	0.	24.30	" "
SW	15	S1	1	0.	40.00	0.	18.40	" "
SW	15	S4	3	0.	40.00	0.	12.30	" "
E1	16	T	23	0.	999.90	0.	5.00	" "
E2	17	T	23	0.	999.90	0.	5.00	" "
M1	18	T	23	0.	999.90	30.00	30.00	" "
M2	19	T	23	0.	999.90	20.00	20.00	" "
I1	20	T	23	0.	999.90	10.00	10.00	" "
I2B	21	T	23	0.	999.90	5.00	5.00	" "
A1	22	T	23	0.	999.90	5.00	5.00	" "
T	23	D	14	0.	999.90	0.	80.00	" "

TOTAL COST IS 10478829. DOLLARS PER YEAR

APPENDIXES

Appendix A

THE STANDARD LINEAR PROGRAMMING MODEL

The following pages present a brief description of the efforts to apply a standard linear programming model and the reasons for abandoning this approach in favor of the network approach.

During this part of the study, a limited-scope model was developed wherein the main elements of a municipal water supply and wastewater disposal situation could be formulated as a conventional linear programming problem. The model concept was to optimize the blends of water from the available sources to provide water for the indicated demands.

STANDARD MODEL DESCRIPTION

An existing computer program – the LP-600 linear programming system, written for the General Electric 635 computer – was adopted for this model to investigate the effects of (1) water availabilities and demands, (2) costs of treatment, and (3) various sets of quality criteria for the different water uses.

Within the linear programming model, the quality of each water source was specified in terms of eight parameters: total dissolved solids (TDS), suspended solids, hardness, chemical oxygen demand (COD), ammonia, total nitrogen, total phosphorus, and coliform bacteria. In addition, minimum quality requirements and removal efficiencies were specified for

each type of water demand and selected treatment process, respectively. Also, an upper limit was placed on the availability of water from all sources with the exception of the seawater source, and a percentage of the municipal demand was specified as the upper limit on the wastewater available for renovation. When applicable, a unit cost was specified in cents per thousand gallons; this cost was independent of the flow rate. No charges were applied for conveyance of water or wastewater in this limited scope model. Each of the above parameters, flows, and costs was identified in the computer program by linear equations and inequalities.

From the specified linear equations and inequalities, this model using the Simplex method of analyzing linear programming problems could generate the least-cost solution of supplying water demands. In addition, sensitivity information could be obtained on the various parameters considered in the model. Unfortunately, this type of model was limited in its applicability as discussed in the following paragraphs.

STANDARD MODEL CAPABILITIES AND LIMITATIONS

The computer program used in this study was capable of analyzing up to 4000 equations or inequalities and had several options for modification of the basic Simplex method that might be utilized for the problem at hand, (e.g., separable programming, decomposition, and generalized upper bounding algorithms). The program was equipped with a matrix generator language that could formulate the linear programming matrix from submatrices and other descriptions of the system. A report generator language was also provided in the program for printing solutions in a desired format.

The most important feature of the standard linear programming approach was the fact that multiple water quality characteristics could be directly incorporated into the basic model framework. However, the time involved

in model formulation and computation increased greatly for each added quality parameter. Also, the source quality, removal efficiencies, and demand requirements could not be defined to the same level of accuracy as for other model elements – such as flows and costs. This introduced a certain bias into the model with respect to the quality considerations that can only be alleviated by extensive efforts in problem formulation and interpretation of the results.

This bias became very apparent after a limited number of runs with the exploratory model discussed above when solutions were generated that were unrealistic from an engineering design standpoint. In a specific case, it was observed that the overall water and wastewater system cost as generated by the program could be substantially decreased by making slight changes to a few of the required quality parameters. Although the solution having the decreased cost was the obvious engineering choice, it was not the solution generated by the program. In another case, the program generated a solution that provided low-grade demands with distilled water and high-grade demands with water from lower-quality sources. It appeared that a solution showing a reversal of this situation would result in the same, or only slightly higher, costs.

The standard linear programming model placed overemphasis on water quality, thus resulting in solutions that were highly dependent on water quality specifications. Such specifications are often quite arbitrary. Consequently, it became more desirable to consider a model formulation where the quality constraints could be evaluated separately from the basic flows and costs. This led to a problem structure for which the network approach is more applicable.

Appendix B

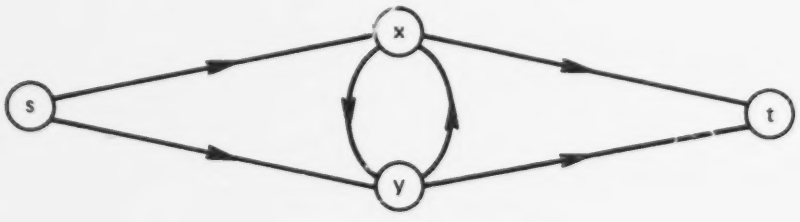
NETWORK THEORY

The following is a discussion of the procedure for minimizing the cost of flows in networks as applied in the mathematical model developed in this study.

NETWORKS

A directed network or directed linear graph, G = (N;A), consists of a collection N of elements x, y – together with a subset A of the ordered pairs (x, y) of elements taken from N. We will assume throughout that N is a finite set, because our interest lies mainly in the construction of computational procedures with practical applications. The elements of N are called nodes or vertices. Members of A are referred to as arcs, branches, or edges. Node-arc terminology will be used here to describe a network.

A network may be pictured by selecting a point corresponding to each node x of N and directing an arrow from x to y if the ordered pair (x, y) is in A, i.e., if flow is admissible from x to y. For example, the network shown below consists of four nodes, s, x, y, and t and six arcs (s, x), (s, y), (x, y), (y, x), (x, t), and (y, t).



Such a network is termed "directed," since each arc allows flow in a specific direction; though it may be possible to have flow in both directions – shown by two arcs in between two nodes.

FLOWS IN NETWORK

Given a network, $G = (N;A)$, it is assumed that each arc $(x, y) \in A$* has associated with it a nonnegative real number $c(x, y)$, called the capacity of the arc (x, y). It may be thought of as representing the maximum amount of some commodity (fluid, electricity, consumer goods, money) that can arrive at y from x per unit time.

Let s and t be two special nodes of N. The node s is called a source that generates flow, and the node t is called a sink that consumes flow. It is also possible to conceive a return arc (t, s) that turns the total flow back from the sink to the source, and a conserving cycling flow is assumed for the network.

A static (steady-state) flow of value v from s to t in the network is a function, $f(x, y)$, that assigns flows in the individual arcs of the network and transmits v units of net flow from s to t in unit time; the flow is conserved for all the nodes in the network except s and t.

This can be expressed as

$$\sum_{a \in N} f(a, x) - \sum_{b \in N} f(x, b) = \begin{cases} v, & x = s \\ 0, & x \neq s, t \\ -v, & x = t \end{cases} \qquad (1)$$

Equation (1) is known as the flow conservation equation. The capacity constraints are expressed for all $(x, y) \in A$ by

$$f(x, y) \leq c(x, y) \qquad (2)$$

*The symbol $\in$ means "belonging to," i.e., $(x, y) \in A$ should be read as (x, y) belonging to the collection A.

One of the common problems connected with flows in networks is to determine the feasibility of a certain flow value v in a capacitated network. A related problem is to find the maximal flow through a capacitated network.

It is plausible to assume a unit cost d (x, y) for flow in arc (x, y) of the network. Another interesting problem with practical application is to find the distribution of flow that minimizes the total cost of transporting a given flow value v through the network, if feasible.

THE GENERAL MINIMAL-COST-FLOW PROBLEM (Ref. 5)

The construction of minimum-cost flows that fulfill demands at some nodes from supplies at others, in a network in which each arc has infinite capacity and a unit shipping cost (assumed nonnegative), has been called the "transshipment problem." The transshipment problem, with capacity constraints on arcs, is also known as the minimum-cost-flow problem. It is well known that such a problem can be converted to a Hitchcock transportation problem. Efficient methods for solving the Hitchcock transportation problem are available; however, a direct solution to the minimum-cost-flow problem is presented below.

It is assumed that a given network (N;A) has sources S, intermediate nodes K, sinks T, arc capacities c (x, y), and arc unit costs d (x, y), with suppiles a(x) at sources $x \in S$ and demands b(x) for $x \in T$. The problem is to construct a feasible flow, if one exists, that minimizes total cost over all the arcs of the network. This problem is formulated as a linear program:

$$f(x, N) - f(N, x) \leq a(x), \quad x \in S \tag{3}$$

$$f(x, N) - f(N, x) = 0, \quad x \in K \tag{4}$$

$$f(x, N) - f(N, x) \leq -b(x), \quad x \in T \tag{5}$$

$$0 \leq f(x, y) \leq c(x, y), \quad (x, y) \in A \tag{6}$$

$$\text{Minimize} \sum_{(x, y) \in A} d(x, y)\ f(x, y) \tag{7}$$

where

$f(x, N) = \sum_{a \in N} f(x, b)$ is the total flow coming out of node x to all the other nodes of the network.

$f(N, x) = \sum_{a \in N} f(a, x)$ is the total flow entering the node x from all other nodes,

and their difference represents the flow generated or consumed (depending on the sign) at node x.

It is assumed for simplification that a (x), b (x), and c (x, y) are positive integers and that d (x, y) are nonnegative integers. This assumption does not limit the solution of practical problems since proper units can be chosen to express these quantities as integers and, ultimately, a digital computer will be used.

It is convenient to put this problem in slightly different terms. First, we shall assume a single source and single sink in the network (N;A). This is done by adding nodes s, t to the original network, together with source and sink arcs (s, S) and (T, t). For the source arcs, c (s, x) = a (x) and d (s, x) = 0, with x belonging to S. For the sink arcs, c (x, t) = b (x) and a (x, t) = 0, with t belonging to T.

Second, we shall introduce the flow value v as an explicit variable in the program.

As the third step, we shall maximize instead of minimizing the function in Eq. (7):

$$p \cdot v - \sum_{(x, y) \in A} d(x, y)\ f(x, y)$$

where p may be thought of as a parameter that assumes the values 0, 1, 2, ... and interpreted as a premium on every unit of flow that gets through the network. Thus, we are now considering a sequential family of related linear programs.

$$f(s, N) - v = 0 \tag{8}$$

$$f(x, N) - f(N, x) = 0 \quad x \neq s, t \tag{9}$$

$$-f(N, t) + v = 0 \tag{10}$$

$$0 \leq f(x, y) \leq c(x, y)\ ,\ (x, y) \in A \tag{11}$$

$$\text{Maximize } p \cdot v - \sum_{(x, y) \in A} d(x, y)\ f(x, y) \tag{12}$$

For a sufficiently large p, the related programs ask for a maximal flow that minimizes cost over all maximal flows. Hence, for large p, a solution either solves the original minimum-cost-flow problem, Eqs. (3) to (7) (if v equals the demand), or shows it to be infeasible.

Before describing the computational process, we consider the dual (Ref. 6) of the pth related linear program. If dual variables $\pi(x)$ are assigned to Eqs. (8) to (10) and $\gamma(x, y)$ to the capacity constraints, Eq. (11), then the dual linear program is expressed as

$$-\pi(s) + \pi(t) = p \tag{13}$$

$$\pi(x) - \pi(y) + \gamma(x, y) \geq -a(x, y),\ (x, y) \in A \tag{14}$$

$$\gamma(x, y) \geq 0\ ,\ (x, y) \in A \tag{15}$$

$$\text{Minimize} \sum_{(x, y) \in A} c(x, y)\ \gamma(x, y) \tag{16}$$

$\pi(x)$ are denoted as node numbers and $\gamma(x, y)$ as arc numbers. The optimality criteria for primal [Eq. (8) to (11)] and dual [Eq. (13) to (16)] linear programs are given by

$$\pi(x) - \pi(y) + \gamma(x, y) > -a(x, y) \Rightarrow f(x, y) = 0^{*} \quad (17)$$

$$\gamma(x, y) > 0 \Rightarrow f(x, y) = c(x, y) \quad (18)$$

It follows that if a flow f and node numbers π can be constructed to satisfy the following equations:

$$\pi(s) = 0, \ \pi(t) = p, \quad (19)$$

$$\pi(y) - \pi(x) < a(x, y) \Rightarrow f(x, y) = 0 \quad (20)$$

$$\pi(y) - \pi(x) > a(x, y) \Rightarrow f(x, y) = c(x, y), \quad (21)$$

then, by taking

$$\gamma(x, y) = \max.[\, 0, \pi(y) - \pi(x) - d(x, y)\,] \quad (22)$$

feasible solutions both to the pth related linear program and to its dual have been found that satisfy Eqs. (17) and (18) and are therefore optimal in their respective programs.

Solution of the Minimal Cost Flow Problem: The Out-of-Kilter Algorithm

Similar to the case for the Hitchcock problem, the minimal cost flow problem could be solved by solving a sequence of maximal flow problems, each on a subnetwork of admissible arcs. However, a more efficient algorithm is available as a standard user package with major computing units. This is known as the out-of-kilter algorithm (Ref. 5), and it has at least three advantages over other computing methods:

*The symbol $\Rightarrow$ means "implies."

- Lower bounds as well as capacities for flows in each arc can be handled directly.
- The cost coefficient for an arc may be arbitrary in sign.
- The method can be initiated with any circulation or flow, feasible or not, and any set of node numbers.

For a flow network with no exogenous flows (this is obtained by adding a return arc to the network connecting sinks to sources), the out-of-kilter algorithm solves the minimum cost circulation (flow) problem.

$$\text{Minimize} \sum_{(x,y)\in A} d(x,y)\, f(x,y) \tag{23}$$

subject to

$$f(x,N) - f(N,x) = 0, \quad \text{all } x \in N \tag{24}$$

and

$$\ell(x,y) \leq f(x,y) \leq c(x,y), \quad \text{all } (x,y) \in A \tag{25}$$

where $\ell(x,y)$ is the lower bound on flow in arc (x,y), the other terms having been defined before.

It is clear that Eqs. (23) to (25) define a linear program. Dual variables $\pi(x)$ for each $x \in N$ may be defined as the set of node prices with $\gamma(x,y)$ corresponding to the constraint $f(x,y) \leq c(x,y)$ and with $\beta(x,y)$ corresponding to $\ell(x,y) \leq f(x,y)$, for each $(x,y) \in A$. Then, the dual linear programming problem for all $(x,y) \in A$ becomes:

$$\text{Maximize} \sum_{(x,y)\in A} \left| -c(x,y)\,\gamma(x,y) + \ell(x,y)\,\beta(x,y) \right| \tag{26}$$

subject to

$$\pi(x) - \pi(y) - \gamma(x,y) + \beta(x,y) = d(x,y) \tag{27}$$

$$\gamma(x,y) \geq 0 \quad , \quad \beta(x,y) \geq 0 \tag{28}$$

The optimality conditions (complementary slackness) for all $(x, y) \in A$ yield

$$d(x, y) + \pi(x) - \pi(y) > 0 \Rightarrow f(x, y) = \ell(x, y) \qquad (29)$$

$$d(x, y) + \pi(x) - \pi(y) < 0 \Rightarrow f(x, y) = c(x, y) \qquad (30)$$

These are necessary and sufficient conditions for a solution (f, π, γ, β) to be optimal for both the primal and dual problems.

The out-of-kilter algorithm, starting with an arbitrary set of prices π and any set of flows f satisfying Eq. (24), builds flow circulations and/or changes node prices in the network with the goal of fulfilling the optimality criteria of Eqs. (29) and (30). Any arc for which either Eq. (29) or (30) is contradicted is said to be out of kilter; otherwise, the arc is in kilter. The algorithm brings out-of-kilter arcs into kilter while maintaining in-kilter arcs in kilter. Eventually, all arcs are put in kilter, or it is learned that certain arcs cannot be in kilter simultaneously; i.e., the problem is infeasible. If all the variables, costs, and flow bounds are required to be in integers, it is easily proven that the algorithm terminates in a finite number of steps. (Ref. 5)

Computational Procedure for Nonlinear Cost Functions

The out-of-kilter algorithm is designed to handle minimum cost network flow problems with linear cost functions. As explained in the main body of the report, the cost functions in the network representing the water distribution and waste treatment system were nonlinear functions of the flows in the arcs. To handle this situation, a recosting subroutine was added to the out-of-kilter algorithm that would reassign unit costs for flows in arcs based on the last solution of the out-of-kilter routine. The problem would be resolved with the new cost data. Usually, good convergence is obtained within a few iterations, as seen by actual computer runs. This procedure is explained in detail in Section 3 of the main body of the report.

Appendix C

COMPUTER PROGRAM LISTINGS

Computer listings are presented in this appendix for the following subroutines:

- Preprocessor to Out of Kilter
- Network Flow Analysis System
- Cost Calculation
- Out-of-Kilter Algorithm
- Sort Input
- Output

```
*PREPRO            PREPROCESSOR TO OUT OF KILTER
*
*
      SUBROUTINE PREPRO
      COMMON  H(1000) , N(1000) , NCST(1000) , IH(1000) , LO(1000)
      COMMON  LFLOW(1000) , IP(1000)
      COMMON  NODES , NRCS
      COMMON  REINIT(1000) , RETERM(1000) , STORE(900)
      COMMON LAB(25),EPS(25),CAP(25,25),FLO(25,25),NCSA(25),NICID(25,25)
      DIMENSION  IDEVC(6) , IEXTRC(6) , ISTOR(7) , IEXTRW(2)
      REAL  INIT
      EQUIVALENCE (1,NRCS)
      DATA  END    / 3HEND    /
      DATA  BLANK / 0377777777777 /
      LOOP = 0
      I = 0
      ICOUNT = 0
    5 LOOP = LOOP + 1
      TOTAL =  0.
      IF (LOOP .GT. 5)  RETURN
      IF (LOOP .NE. 1)  GO TO 20
    1 I = I + 1
      ICOUNT = ICOUNT + 1
      READ (5,950)  TEST
  950 FORMAT (A6)
      IF (TEST .EQ. END   ) GO TO 880
      CALL REREAD(5)
*
*        INPUT ARCH CARDS
*
      READ (5,901)  INIT , TERM , MAXFLO , MINFLO , ASMFLO , DISTA ,
     1     DISTB , DISTC , ELEV , NOCSTF , ICSUPM , ICSUPA ,
     2     (IDEVC(K) , K=1,6) , (IEXTRC(K),K=1,6) , (ISTOR(K),K=1,7) ,
     3     ICSWTR , ICGTCL , ICGTDM , ICSWSF , ICP , ICAS , ICF , ICPNC
     4     , ICED , ICTF , ICCAD , ICPN , ICIJ
     5     , ICSEW , (IEXTRW(K) , K=1,2) , ICSD , ICCON , INDC , ICSTOR
  901 FORMAT (2A4 ,2F4.4F4.1,F4.0 , 42I1)
      GO TO 100
   20 IJ = IJ + 1
      ICOUNT = ICOUNT + 1
      READ (4)  TEST
      IF (TEST .EQ. END   ) GO TO 890
      CALL REREAD(4)
      READ (4)      INIT , TERM , MAXFLO , MINFLO , ASMFLO , DISTA ,
     1     DISTB , DISTC , ELEV , NOCSTF , ICSUPM , ICSUPA ,
     2     (IDEVC(K) , K=1,6) , (IEXTRC(K),K=1,6) , (ISTOR(K),K=1,7) ,
     3     ICSWTR , ICGTCL , ICGTDM , ICSWSF , ICP , ICAS , ICF , ICPNC
     4     , ICED , ICTF , ICCAD , ICPN , ICIJ
     5     , ICSEW , (IEXTRW(K) , K=1,2) , ICSD , ICCON , INDC , ICSTOR
*****************************************
*        CALCULATE COST ITEMS
*****************************************
  100 CONTINUE
      COST   = 0.
      CFEED  = 0.
      CSUPM  = 0.
      CSUPA  = 0.
      CSWTR  = 0.
      CGTCL  = 0.
      CGTDM  = 0.
      CSWSF  = 0.
      CP     = 0.
      CAS    = 0.
      CF     = 0.
      CPNC   = 0.
      CED    = 0.
      CTF    = 0.
      CCAD   = 0.
      CPN    = 0.
      CIJ    = 0.
      CSEW   = 0.
```

```
      CSD    = 0.
      CCON   = 0.
      CIND   = 0.
      CSTOR  = 0.
*
*        FLOW ADDITION
*
      IF (NOCSTF .EQ. 0)  GO TO 300
      COST = COST + CFEED
*
*        SOURCE DEVELOPMENT
*
  300 CONTINUE
*
*        MUNICIPAL CONVEYANCE
*
      IF (ICSUPM .EQ. 0)  GO TO 301
      CSUPM= 9.2
      COST = COST + CSUPM
*
*        AGRICULTURAL CONVEYANCE
*
  301 IF (ICSUPA .EQ. 0)  GO TO 310
      CSUPA= 7.8
      COST = COST + CSUPA
*
*        RAW WATER TREATMENT
*
  310 CONTINUE
      IF (ICSWTR .EQ. 0 )  GO TO 320
      IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
      IF (ASMFLO .GT. 10.0)  GO TO 311
      CSWTR = CALC(15.4,8.0,1.0,10.0,ASMFLO)
      GO TO 312
  311 CSWTR = CALC(8.0,5.3,10.0,100.0,ASMFLO)
  312 COST = COST + CSWTR
*
*        GROUND WATER CHLORINE TREATMENT
*
  320 IF (ICGTCL .EQ. 0)  GO TO 330
      IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
      CGTCL = CALC(0.82,0.44,1.0,100.0,ASMFLO)
      COST = COST + CGTCL
*
*        GROUND WATER TREATMENT DEMINER
*
  330 IF (ICGTDM .EQ. 0)  GO TO 340
      CGTDM=2.5
      COST = COST + CGTDM
*
*
*        SURFACE WATER TREATMENT WITH SOFTENER
  340 IF (ICSWSF .EQ. 0)  GO TO 350
      IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
      IF (ASMFLO .GT. 10.0)  GO TO 345
      CSWSF = CALC(19.4,12.0,1.0,10.0,ASMFLO)
      GO TO 346
  345 CSWSF = CALC(12.0,9.3,10.0,100.0,ASMFLO)
  346 COST = COST + CSWSF
*
*        RENOVATION AND WATER TREATMENT
*
*             PRIMARY
*
  350 IF (ICP .EQ. 0 )  GO TO 410
      IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
      CP = CALC(12.4,4.1,1.0,100.0,ASMFLO)
      COST = COST + CP
*
*             ACTIVATED SLUDGE
*
  410 IF (ICAS .EQ. 0 )  GO TO 415
```

```
144             IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
145             CAS = CALC(20.9,7.4,1.0,100.0,ASMFLO)
146             COST = COST + CAS
147       *
148       *                SAND FILTRATION
149       *
150           415 IF (ICF .EQ. 0 )  GO TO 420
151             IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
152             CF = CALC(6.7,1.2,1.0,100.0,ASMFLO)
153             COST = COST + CF
154       *
155       *                PHOSPHORUS,NITROGEN, AND CARBON FILTRATION
156       *
157           420 IF (ICPNC .EQ. 0 )  GO TO 430
158             IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
159             IF (ASMFLO .GT. 10.0)  GO TO 421
160             CPNC = CALC(57.4,21.9,1.0,10.0,ASMFLO)
161             GO TO 422
162           421 CPNC = CALC(21.8,14.3,10.0,100.0,ASMFLO)
163           422 COST = COST + CPNC
164       *
165       *                ELECTRODIALYSIS
166       *
167           430 IF (ICED .EQ. 0 )  GO TO 440
168             IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
169             CED = CALC(23.7,10.2,1.0,100.0,ASMFLO)
170             COST = COST + CED
171       *
172       *          TRICKLING FILTER
173       *
174           440 IF (ICTF .EQ. 0)  GO TO 441
175             IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
176             CTF = CALC(17.4,5.4,1.0,100.0,ASMFLO)
177             COST = COST + CTF
178       *
179       *          CARBON ADSORPTION
180       *
181           441 IF (ICCAD .EQ. 0)  GO TO 444
182             IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
183             IF (ASMFLO .GT. 10.0)  GO TO 442
184             CCAD = CALC(25.9,11.3,1.0,10.0,ASMFLO)
185             GO TO 443
186           442 CCAD = CALC(11.3,7.2,10.0,100.0,ASMFLO)
187           443 COST = COST + CCAD
188       *
189       *          PHOSPHORUS AND NITROGEN REMOVAL
190       *
191           444 IF (ICPN .EQ. 0)  GO TO 447
192             IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
193             IF (ASMFLO .GT. 10.0)  GO TO 445
194             CPN = CALC(31.5,10.5,1.0,10.0,ASMFLO)
195             GO TO 446
196           445 CPN = CALC(10.9,7.1,10.0,100.0,ASMFLO)
197           446 COST = COST + CPN
198       *
199       *          GROUND WATER INJECTION
200       *
201           447 IF (ICIJ .EQ. 0)  GO TO 450
202           448 CIJ=5.0
203           449 COST = COST + CIJ
204       *
205       *          WASTE WATER CONVEYANCE
206       *
207           450 IF (ICSEW .EQ. 0)  GO TO 460
208             IF (ASMFLO .LT. 0.1)  ASMFLO = 0.1
209             CA = (2.15 * ASMFLO**(-0.544) +(0.326 / ASMFLO)) * DISTA
210             CB = (1.49 * ASMFLO**(-0.544) + (0.074 / ASMFLO)) * DISTB
211             CC = (0.99 * ASMFLO**(-0.544) + (0.031 /ASMFLO)) * DISTC
212             CPO=(7.92*(DISTA+DISTB+DISTC)+ELEV)*(0.00565+
213            10.028*ASMFLO**(-0.223))
214             CSEW = 0.75 * (CA + CB + CC) + CPO
215             COST = COST + CSEW
```

```
216       *
217       *        SEAWATER DISTILLATION
218       *
219         461 IF (ICSD .EQ. 0 )  GO TO 470
220             IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
221             IF (ASMFLO .GT. 5.0)  GO TO 462
222             CSD = CALC(108.0,66.0,1.0,5.0,ASMFLO)
223             GO TO 463
224         462 CSD = CALC(66.0,47.5,5.0,100.0,ASMFLO)
225         463 COST = COST + CSD
226       *
227       *        CONVEYANCE OF TREATED WATER
228       *
229         471 IF (ICCON .EQ. 0)  GO TO 520
230             IF (ASMFLO .LT. 0.1)  ASMFLO = 0.1
231             CA = (2.15 * ASMFLO**(-0.544) +(0.326 / ASMFLO)) * DISTA
232             CB = (1.49 * ASMFLO**(-0.544) + (0.074 / ASMFLO)) * DISTB
233             CC = (0.99 * ASMFLO**(-0.544) + (0.031 /ASMFLO)) * DISTC
234             CPQ=(7.92*(DISTA+DISTB+DISTC)+ELEV)*(0.00565*
235            10.028*ASMFLO**(-0.223))
236             CCON=CA+CB+CC+CPQ
237             COST = COST + CCON
238       *
239       *        INDUSTRIAL TREATMENT
240       *
241         520 IF (INDC .EQ. 0)  GO TO 525
242             IF (ASMFLO .LT. 0.5)  ASMFLO = 0.5
243             IF (ASMFLO .GT. 10.0)  GO TO 521
244             CIND = CALC(43.3,23.2,1.0,10.0,ASMFLO)
245             GO TO 522
246         521 CIND = CALC(23.2,14.8,10.0,100.0,ASMFLO)
247         522 COST = COST + CIND
248       *
249       *        TREATED WATER STORAGE
250       *
251         525 IF (ICSTOR .EQ. 0)  GO TO 530
252             IF (ASMFLO .LT. 0.1)  ASMFLO = 0.1
253             IF (ASMFLO .GT. 10.0)  GO TO 526
254             CSTOR = CALC(1.45,0.18,0.1,10.0,ASMFLO)
255             GO TO 527
256         526 CSTOR = CALC(0.18,0.15,10.0,100.0,ASMFLO)
257         527 COST = COST + CSTOR
258       *
259       *
260       *
261         530 IF (ICOUNT .GT. 24)  ICOUNT = 1
262             IF (ICOUNT .NE. 1)  GO TO 810
263         800 WRITE (6,910)
264         910 FORMAT (1H1 , 44X , 43HECONOMICS OF COMBINED SEAWATER DISTILLATION
265            1       //   , 49X , 33HAND WASTEWATER RENOVATION SYSTEMS
266            2       //   , 50X , 31HNETWORK MODEL--BASIC INPUT DATA   ////)
267             WRITE (6,911)
268         911 FORMAT (123H  INIT. TERM.   MAX   MIN   ASS. UNIT    DISTANCE    E
269            1LEV.         UNIT COSTS (C/KG) FOR INDIVIDUAL COST ITEMS
270            2     /   57H  NODE  NODE    FLOW  FLOW  FLOW COST     (MILES)
271            3FT)    /
272            4         128H                (MGD) (MGD) (MGD)(C/KG)  A     B     C
273            5    CSUPH CSUPA CSWTR   CP   CAS   CF   CPNC CED  CSEW CSD  CCON CIN
274            6D CSTOR   )
275         810 FLOMAX = MAXFLO
276             FLOMIN = MINFLO
277             FLOMAX = FLOMAX / 10.
278             FLOMIN = FLOMIN / 10.
279             WRITE (3)INIT , TERM ,COST, MAXFLO , MINFLO , ASMFLO , DISTA ,
280            1      DISTB , DISTC , ELEV , NOCSTF , ICSUPH , ICSUPA ,
281            2      (IDEVC(K) , K=1,6) , (IEXTRC(K),K=1,6) , (ISTOR(K),K=1,7) ,
282            3      ICSWTR , ICGTCL , ICGTDH , ICSWSF , ICP , ICAS , ICF , ICPNC
283            4      , ICED , ICTF , ICCAD , ICPN , ICIJ
284            5      , ICSEW , (IEXTRW(K) , K=1,2) , ICSD , ICCON , INDC , ICSTOR
285             IF (FLOMAX .EQ. 0.)  FLOMAX = BLANK
286             IF (FLOMIN .EQ. 0.)  FLOMIN = BLANK
287             IF (ASMFLO    .EQ. 0.)  ASMFLO    = BLANK
```

```
      IF (COST    .EQ. 0.)  COST    = BLANK
      IF (DISTA .EQ. 0.)  DISTA = BLANK
      IF (DISTB .EQ. 0.)  DISTB = BLANK
      IF (DISTC .EQ. 0.)  DISTC = BLANK
      IF (ELEV  .EQ. 0.)  ELEV  = BLANK
      IF (CFEED .EQ. 0.)  CFEED = BLANK
      IF (CSUPM .EQ. 0.)  CSUPM = BLANK
      IF (CSUPA .EQ. 0.)  CSUPA = BLANK
      IF (CSWTR .EQ. 0.)  CSWTR = BLANK
      IF (CGTCL .EQ. 0.)  CGTCL = BLANK
      IF (CGTDM .EQ. 0.)  CGTDM = BLANK
      IF (CSWSF .EQ. 0.)  CSWSF = BLANK
      IF (CP    .EQ. 0.)  CP    = BLANK
      IF (CAS   .EQ. 0.)  CAS   = BLANK
      IF (CF    .EQ. 0.)  CF    = BLANK
      IF (CPNC  .EQ. 0.)  CPNC  = BLANK
      IF (CED   .EQ. 0.)  CED   = BLANK
      IF (CTF   .EQ. 0.)  CTF   = BLANK
      IF (CCAD  .EQ. 0.)  CCAD  = BLANK
      IF (CPN   .EQ. 0.)  CPN   = BLANK
      IF (CIJ   .EQ. 0.)  CIJ   = BLANK
      IF (CSEW  .EQ. 0.)  CSEW  = BLANK
      IF (CSD   .EQ. 0.)  CSD   = BLANK
      IF (CCON  .EQ. 0.)  CCON  = BLANK
      IF (CIND  .EQ. 0.)  CIND  = BLANK
      IF (CSTOR .EQ. 0.)  CSTOR = BLANK
      WRITE (6,912)  INIT    , TERM    , FLOMAX , FLOMIN ,
     1      ASMFLO    ,COST    ,DISTA , DISTB , DISTC , ELEV , CSUPM ,
     2      CSUPA , CSWTR , CP , CAS , CF , CPNC , CED , CSEW , CSD ,
     3      CCON , CIND , CSTOR
  912 FORMAT(1H0,1X,2(A4,2X), 3(1X,F5.1) , F6.2 , 3F5.1 , F5.0 ,
     1      3(F5.1,1X) , 10F5.1)
      IF (LOOP .NE. 1)  GO TO 20
      GO TO 1
   88 I = I - 1
   89 REWIND 4
      REWIND 3
      CALL FLO41  (LOOP,NCNT,TOTAL)
      PRINT  913,  LOOP , NCNT , TOTAL
  913 FORMAT (12H DURING LOOP  , I4 , 2H ,  , I4 , 20H ITERATIONS ARE RU
     1N, 5X , 14HTOTAL COST IS   , F10.0 , 18H  DOLLARS PER YEAR  )
      NCNT = 0
      IJ = 0
      ICOUNT = 0
      IF (LOOP .EQ. 1)  GO TO 892
      RATIO = (TOTAL1 - TOTAL) / TOTAL
      IF (ABS(RATIO) .LE. 0.02 .AND. LOOP .GT. 2)  RETURN
  892 TOTAL1 = TOTAL
      GO TO 5
      END
```

```
      NETWRK   *********NETWORK FLOW ANALYSIS SYSTEM**********************
      C
      C        MODIFIED BY DAVID YUEN , OCTOBER , 1969
      C     HOOLSEYS WEB IS A GENERALIZED NETWORK FLOW ANALYSIS SYSTEM
      C     IT HAS THE FOLLOWING CAPABILITIES
      C     A SHORTEST PATH ALGORITHM ,FROM NODE ONE TO ALL OTHERS
      C     A MAX-FLOW/ MIN-CUT ALGORITHM
      C     AN OUT OF KILTER ALGORITHM
      C     A MINIMAL SPANNING TREE ALGORITHM
      C
      C     PROBLEM DECKS ARE SET UP AS FOLLOWS
      C     THE FIRST CARD MUST BE AN ALGORITHM REQUEST CARD, STARTING IN
      C     CARD COLUMN ONE AND BEING ONE OF THE FOLLOWING
      C     OUT OF KILTER
      C     MAX FLOW/MIN CUT
      C     SHORTEST PATH
      C     MINIMAL SPANNING TREE
      C
      C     THE SECOND CARD MUST BE A TITLE CARD IN FREE FIELD
      C     THE CONTENTS OF THIS CARD WILL APPEAR ON EVERY PAGE OF THE OUTPUT
      C
      C     THE NEXT CARDS ARE DATA ENTRY CARDS
      C     ALL DATA ENTRY CARDS OPERATE ON 10 COLUMN  FIELDS
      C     CARD COLUMNS  1-10 = STARTING NODE OF ARC ,NUMERIC,RIGHT JUSTIFIED
      C     CARD COLUMNS 11-20 = ENDING   NODE OF ARC ,NUMERIC,RIGHT JUSTIFIED
      C
      C     ALL FOLLOWING  10-CHARACTER FIELDS ARE IN F10.2 SPECIFICATION
      C     (FLOATING POINT) TO ALLOW PLACEMENT ANYWHERE IN THE FIELD
      C     **WARNING** HOWEVER ALL DATA INPUT TO THIS PROGRAM WILL BE PUT
      C     INTO FIXED POINT IMMEDIATELY, WITH POSSIBLE TRUNCATION
      C
      C     FOR THE SHORTEST PATH AND MINIMAL SPANNING TREE ALGORITHMS
      C     CARD COLUMNS 21-30 = ARC LENGTH
      C
      C     FOR THE MAX FLOW/MIN CUT ALGORITHM
      C     CARD COLUMNS 21-30 = ARC CAPACITY
      C     CARD COLUMNS 31-40 = FLOW IN THE ARC
      C
      C     FOR THE OUT OF KILTER ALGORITHM
      C     CARD COLUMNS  1- 4 = INITIAL NODE
      C     CARD COLUMNS  5- 8 = TERMINAL NODE
      C     CARD COLUMNS  9-12 = UPPER BOUND
      C     CARD COLUMNS 13-16 = LOWER BOUND
      C     CARD COLUMNS 17-20 = ASSUMED FLOW
      C     CARD COLUMNS 21-24 = DISTANCE TYPE A (MILE)
      C     CARD COLUMNS 25-28 = DISTANCE TYPE B (MILE)
      C     CARD COLUMNS 29-32 = DISTANCE TYPE C (MILE)
      C     CARD COLUMNS 33-36 = ELEVATION (FEET)
      C     INPUT THE FOLLOWING ITEMS WITH A VALUE 1 IF THAT ITEM IS
      C     INCLUDED IN THE COST CALCULATIONS . OTHERWISE , LEAVE
      C     THE ITEM BLANK
      C     CARD COLUMN 37 = FLOW ADDITION
      C     CARD COLUMN 38 = MUNICIPAL SOURCE DEVELOPMENT AND RAW WATER CONVEYANCE
      C     CARD COLUMN 39 = AGRICULTURAL SOURCE DEVELOPMENT AND RAW WATER CONVEYA
      C     CARD COLUMN 59 = SURFACE WATER TREATMENT WITHOUT SOFTENING
      C     CARD COLUMN 60 = GROUND WATER TREATMENT WITH CHLORINE
      C     CARD COLUMN 61 = GROUND WATER TREATMENT WITH DEMINER
      C     CARD COLUMN 62 = SURFACE WATER TREATMENT WITH SOFTENER
      C     CARD COLUMN 63 = PRIMARY TREATMENT
      C     CARD COLUMN 64 = ACTIVATED SLUDGE TREATMENT
      C     CARD COLUMN 65 = SAND FILTRATION
      C     CARD COLUMN 66 = PHOSPHORUS , NITROGEN , AND CARBON FILTRATION
      C     CARD COLUMN 67 = ELECTRODIALYSIS
      C     CARD COLUMN 68 = TRICKLING FILTER AND PRIMARY TREATMENT
      C     CARD COLUMN 69 = CARBON ADSORPTION
      C     CARD COLUMN 70 = PHOSPHORUS AND NITROGEN REMOVAL
      C     CARD COLUMN 71 = GROUND WATER INJECTION
      C     CARD COLUMN 72 = WASTE WATER CONVEYENCE
      C     CARD COLUMN 75 = SEAWATER DISTILLATION
      C     CARD COLUMN 76 = TREATED WATER CONVEYENCE
      C     CARD COLUMN 77 = INDUSTRIAL WATER TREATMENT
      C     CARD COLUMN 78 = TREATED WATER STORAGE
```

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      C
      C     DATA FOR A PROBLEM IS ENDED WITH AN END CARD AS FOLLOWS
      C     CARD COLUMNS 1-3 = END
      C     THE END OF ALL  PROBLEMS IS SIGNALED BY AN EXIT CARD AS FOLLOWS
      C     CARD COLUMNS 1-4 = EXIT
      C
            COMMON/DATA/ ITLE(20)
            DATA III/3HOUT/,II2/3HMAX/,II3/4HMINI/,II4/4HSHOR/,II5/4HEXIT/
            IIN = 5
            IOT = 6
      C     READ IN AGENDUM CARD AND GO GET THE DESIRED ROUTINE
      100   READ (IIN,1) IWRD
            IF(IWRD.EQ.II5   ) GO TO 999
      C     READ IN TITLE CARD
            READ(IIN,1)(ITLE(I),I=1,20)
      1     FORMAT(20A4)
            IF(IWRD.EQ.III   ) GO TO 101
            IF(IWRD.EQ.II2   ) GO TO 102
            IF(IWRD.EQ.II3   ) GO TO 103
            IF(IWRD.EQ.II4   ) GO TO 104
            WRITE(IOT,2)
      2     FORMAT(68H REQUESTED ALGORITHM NOT IN DICTIONARY, PROGRAM DUMPED O
           1FF MACHINE   )
      101   CALL PREPRO
            GO TO 100
      102   CALL NETA
            GO TO 100
      103   CALL SHRTST(1)
```

```
      NETFLO            OUT OF KILTER  ALGORITHM
            SUBROUTINE NETFLO (INFES,NCNT)
            COMMON  I(1000) , J(1000) , COST(1000) , HI(1000) , LO(1000)
            COMMON  FLOW(1000) , PI(1000)
            COMMON  NODES , ARCS
            COMMON  REINIT(1000) , RETURN(1000) , STORE(500)
            COMMON LAB(25),APS(25),CAP(25,25),FLO(25,25),SCAN(25),NICID(25,25)
            DIMENSION  NA(1000) , NB(1000)
            INTEGER SCAN
            INTEGER A,AOK,C,COK,DEL,E,EPS,INF,LAB,N,NI,NJ,SRC,SNK,
           1FLOW,PI,NA, NODES,ARCS,I,J,COST,HI,LO,NB
            LOGICAL INFES
      C     CHECK FEASIBILITY OF FORMULATION
            INFES = .FALSE.
            DO 161 K=1,1000
      161   NA(K)=0
            DO 10 A=1,ARCS
            IF(LO(A).GT.HI(A)) GO TO 39
      10    CONTINUE
      C     SET INF TO MAX AVAILABLE INTEGER
       16       INF=9999
                AOK=0
      C     FIND OUT OF KILTER ARC
       20   DO 21 A=1,ARCS
            IA=I(A)
            JA = J(A)
               C=COST(A)+PI( IA )-PI( JA )
            IF((FLOW(A).LT.LO(A)).OR.(C.LT.0.AND.FLOW(A).LT.HI(A))) GO TO 22
            IF((FLOW(A).GT.HI(A)).OR.(C.GT.0.AND.FLOW(A).GT.LO(A))) GO TO 23
      21    CONTINUE
      C     NO REMAINING OUT OF KILTER ARCS
            GO TO 38
       22       SRC=J(A)
                SNK=I(A)
                E=+1
            GO TO 24
       23       SRC=I(A)
                SNK=J(A)
                E=-1
            GO TO 24
```

```
C     ATTEMPT TO BRING OUT OF KILTER ARCS INTO KILTER
 24   IF((A.EQ.AOK).AND.(NA(SRC).NE.0)) GO TO 25
          AOK=A
      DO 26 N=1,NODES
          NA(N)= 0
          NB(N)=0
          NA(SRC)=IABS(SNK)+E
 26       NB(SRC)=IABS(AOK)+E
 25       COK=C
 27       LAB=0
      DO 30 A=1,ARCS
      IA=I(A)
      JA = J(A)
      IF((NA(IA).EQ.0.AND.NA(JA).EQ.0).OR.(NA(IA).NE.0 .AND.NA(JA).NE.0)
     1GO TO 30
      C= COST(A)+PI(IA) - PI(JA)
      IF(NA(IA).EQ.0) GO TO 28
      IF(FLOW(A).GE.HI(A).OR.(FLOW(A).GE.LO(A).AND.C.GT.0))GO TO 30
      NA(JA) = I(A)
      NB(JA) = A
      GO TO 29
   28 IF(FLOW(A).LE.LO(A).OR.(FLOW(A).LE.HI(A).AND.C.LT.0))GO TO 30
      IA = I(A)
      NA(IA) = -J(A)
      NB(IA) = -A
   29 LAB = 1
C NODE LABELED, TEST FOR BREAKTHRU
      IF(NA(SNK).NE.0) GO TO 33
   30 CONTINUE
C NO BREAKTHRU
      IF(LAB.NE.0) GO TO 27
C DETERMINE CHANGE TO PI VECTOR
      DEL = INF
      DO 31 A=1,ARCS
      IA = I(A)
      JA =J(A)
      IF((NA(IA).EQ.0.AND.NA(JA).EQ.0).OR.(NA(IA).NE.0.AND.NA(JA).NE.0))
     1GO TO 31
      C=COST(A)+PI(IA)-PI(JA)
      IF(NA(JA).EQ.0.AND.FLOW(A).LT.HI(A)) DEL= MIN0(DEL,C)
      IF(NA(JA).NE.0.AND.FLOW(A).GT.LO(A)) DEL= MIN0(DEL,-C)
   31 CONTINUE
      IF(DEL.EQ.INF.AND.(FLOW(AOK).EQ.HI(AOK).OR.FLOW(AOK).EQ.LO(AOK)))
     1DEL=ABS(COK)
      IF(DEL.EQ.INF) GO TO 39
C EXIT, NO FEASIBLE FLOW PATTERN
C CHANGE PI VECTOR BY COMPUTED DEL
      DO 32 N=1,NODES
      IF(NA(N).EQ.0) PI(N)=PI(N)+DEL
 32   CONTINUE
C FIND ANOTHER OUT-OF-KILTER ARC
      GO TO 20
C BREAKTHRU, COMPUTE INCREMENTAL FLOW
   33 EPS=INF
      NI=SNK
   34 NJ=IABS(NA(NI))
      A=IABS(NB(NI))
      C=COST(A)-ISIGN(IABS(PI(NI) -PI(NJ)),NB(NI))
      IF(NB(NI).LT.0) GO TO 35
      IF(C.GT.0.AND.FLOW(A).LT.LO(A)) EPS=MIN0(EPS,LO(A)-FLOW(A))
      IF(C.LE.0.AND.FLOW(A).LT.HI(A)) EPS=MIN0(EPS,HI(A)-FLOW(A))
      GO TO 36
   35 IF(C.LT.0.AND.FLOW(A).GT.HI(A)) EPS=MIN0(EPS,FLOW(A)-HI(A))
      IF(C.GE.0.AND.FLOW(A).GT.LO(A)) EPS=MIN0(EPS,FLOW(A)-LO(A))
   36 NI=NJ
      IF(NI.NE.SRC) GO TO 34
C CHANGE FLOW VECTOR BY COMPUTED EPS
   37 NJ=IABS(NA(NI))
      A=IABS(NB(NI))
      FLOW(A)=FLOW(A)+ISIGN(EPS,NB(NI))
      NI=NJ
      IF(NI.NE.SRC) GO TO 37
```

```
C FIND ANOTHER OUT OF KILTER ARC
*     CALL OUTPUT(4,0,2,0)
      NCNT = NCNT + 1
      AOK=0
      GO TO 20
   39     INFES=.TRUE.
   38 CONTINUE
      RETURN
      END
```

```
CFLOW1              SORT INPUT
      SUBROUTINE FLOW1   (LOOP,NCNT,TOTAL)
      COMMON  I(1000) , J(1000) , COST(1000) , HI(1000) , LO(1000)
      COMMON  FLOW(1000) , PI(1000)
      COMMON  NODES , ARCS
      COMMON  REINIT(1000) , RETERM(1000) , STORE(500)
      COMMON LAB(25),APS(29),CAP(25,25),FLO(25,29),SCAN(25),NICIO(25,25)
      DIMENSION  NA(1000) , NB(1000)
      DIMENSION  IDEVC(6) , IEXTRC(6) , ISTOR(7) , IEXTRW(2)
      INTEGER A,ACK,C,COK,DEL,E,EPS,INF,LAP,N,NI,NJ,SRC,SNK,
     1FLOW,PI,NA,NODES,ARCS,I,J,COST,HI,LO,NB
      INTEGER SCAN
      REAL INIT
      EQUIVALENCE (I,J,ARCS)
      EQUIVALENCE (ISTORE,NODES)
      LOGICAL INFES
      DATA  END    / 3HEND    /
  101 FORMAT(2I5)
  105 FORMAT(8(I6,I4))
  110 FORMAT(8I10)
  115 FORMAT(19H1NUMBER OF NODES = ,I5,/,18H NUMBER OF ARCS = ,I5,//,5X,
     11HM,5X,1HI,5X,1HJ,6X,4HCOST,10X,2HHI,11X,2HLO,//,(3(2X,I4),
     13(3X,I10)))
      IF (LOOP .NE. 1)  GO TO 140
      DO 108 JR=1,1000
      I   (JR)=0
      J   (JR)=0
      HI  (JR)=0
      LO  (JR)=0
      COST(JR)=0
  108 FLOW(JR)=0
      II = 0
      ISTORE = 0
      DO 72   L=1,IJ
      READ (3) INIT , TERM , CST, MAXFLO , MINFLO , ASMFLO , DISTA ,
     1     DISTB , DISTC , ELEV , NOCSTF , ICSUPH , ICSUPA ,
     2     (IDEVC(K) , K=1,6) , (IEXTRC(K),K=1,6) , (ISTOR(K),K=1,7) ,
     3     ICSWTR , ICOTCL , ICGTDM , ICSWSF , ICP , ICAS , ICF , ICPNC
     4     , ICED , ICTF , ICCAD , ICPN , ICIJ
     5     , ICSEW , (IEXTRW(K) , K=1,2) , ICSD , ICCON , INDC , ICSTOR
      DO 73   K1=1,ISTORE
      IF (INIT     .EQ. STORE(K1))  GO TO 72
   73 CONTINUE
      ISTORE = ISTORE + 1
      STORE(ISTORE) = INIT
   72 CONTINUE
      REWIND 3
      DO 82   K1=1,ISTORE
```

```
      DO 83   L=1,IJ
      READ (3) INIT , TERM , CST, MAXFLO , MINFLO , ASMFLO , DISTA ,
     1     DISTB , DISTC , ELEV , NOCSTF , ICSUPM , ICSUPA ,
     2     (IDEVC(K) , K=1,6) , (IEXTRC(K),K=1,6) , (ISTOR(K),K=1,7) ,
     3     ICSWTR , ICOTCL , ICGTDM , ICSWSF , ICP , ICAS , ICF , ICPNC
     4     , ICED , ICTF , ICCAD , ICPN , ICIJ
     5     , ICSEW , (IEXTRW(K) , K=1,2) , ICSD , ICCON , INDC , ICSTOR
      IF (INIT     .NE. STORE(K1))  GO TO 83
      II = II + 1
      RETINIT(II) = INIT
      RETERM(II) = TERM
      COST(II) =  CST  * 100.
      HI(II) = MAXFLO
      LO(II) = MINFLO
      I(II) = K1
      WRITE (2)      INIT , TERM , MAXFLO , MINFLO , ASMFLO , DISTA ,
     1     DISTB , DISTC , ELEV , NOCSTF , ICSUPM , ICSUPA ,
     2     (IDEVC(K) , K=1,6) , (IEXTRC(K),K=1,6) , (ISTOR(K),K=1,7) ,
     3     ICSWTR , ICOTCL , ICGTDM , ICSWSF , ICP , ICAS , ICF , ICPNC
     4     , ICED , ICTF , ICCAD , ICPN , ICIJ
     5     , ICSEW , (IEXTRW(K) , K=1,2) , ICSD , ICCON , INDC , ICSTOR
   83 CONTINUE
      REWIND 3
   82 CONTINUE
      REWIND 2
      DO 92   K=1,IJ
      DO 93   K1=1,ISTORE
      IF (RETERM(K) .EQ. STORE(K1))  GO TO 91
   93 CONTINUE
      ISTORE = ISTORE + 1
      STORE(ISTORE) = RETERM(K)
      J(K) = ISTORE
      GO TO 92
   91 J(K) = K1
   92 CONTINUE
      GO TO 160
  140 DO 150  L=1,ARCS
      READ (3) INIT , TERM , CST, MAXFLO , MINFLO , ASMFLO , DISTA ,
     1     DISTB , DISTC , ELEV , NOCSTF , ICSUPM , ICSUPA ,
     2     (IDEVC(K) , K=1,6) , (IEXTRC(K),K=1,6) , (ISTOR(K),K=1,7) ,
     3     ICSWTR , ICOTCL , ICGTDM , ICSWSF , ICP , ICAS , ICF , ICPNC
     4     , ICED , ICTF , ICCAD , ICPN , ICIJ
     5     , ICSEW , (IEXTRW(K) , K=1,2) , ICSD , ICCON , INDC , ICSTOR
      FLOW( L) = 0
      COST( L) =  CST  * 100.
  150 CONTINUE
  160 CONTINUE
      DO 10 M=1,NODES
   10 PI(M)=0
      CALL OUTPUT(1,0,2,0)
      CALL NETFLO (IPASS,NCNT)
      DO 95  L=1,ARCS
      READ (2)      INIT , TERM , MAXFLO , MINFLO , ASMFLO , DISTA ,
     1     DISTB , DISTC , ELEV , NOCSTF , ICSUPM , ICSUPA ,
     2     (IDEVC(K) , K=1,6) , (IEXTRC(K),K=1,6) , (ISTOR(K),K=1,7) ,
     3     ICSWTR , ICOTCL , ICGTDM , ICSWSF , ICP , ICAS , ICF , ICPNC
     4     , ICED , ICTF , ICCAD , ICPN , ICIJ
     5     , ICSEW , (IEXTRW(K) , K=1,2) , ICSD , ICCON , INDC , ICSTOR
      ASMFLO = FLOW(L)
      ASMFLO = ASMFLO / 10.
      CST = COST(L)
      CST = CST / 100.
      TOTAL = TOTAL + CST  * ASMFLO * 3650.
      WRITE (4)      INIT , TERM , MAXFLO , MINFLO , ASMFLO , DISTA ,
     1     DISTB , DISTC , ELEV , NOCSTF , ICSUPM , ICSUPA ,
     2     (IDEVC(K) , K=1,6) , (IEXTRC(K),K=1,6) , (ISTOR(K),K=1,7) ,
     3     ICSWTR , ICOTCL , ICGTDM , ICSWSF , ICP , ICAS , ICF , ICPNC
     4     , ICED , ICTF , ICCAD , ICPN , ICIJ
     5     , ICSEW , (IEXTRW(K) , K=1,2) , ICSD , ICCON , INDC , ICSTOR
   95 CONTINUE
      WRITE (4)  END
      REWIND 2
```

```
      REWIND 3
      REWIND 4
      IF (INFES)         PRINT 120 , LOOP
      CALL OUTPUT(2,0,2,0)
      IF (INFES)   CALL EXIT
120   FORMAT(      33H SOLUTION INFEASIBLE DURING LOOP  , I4 )
125   FORMAT(///16H ARC    FLOW(ARC)  ,/,(1X,I4,2X,I10))
130   FORMAT(///17H NODE     PI(NODE)  ,/,(1X,I4,2X,I10))
      RETURN
      END
```

```
      SUBROUTINE OUTPUT(K,NN,IWHR,KK)
      COMMON  H(1000) , N(1000) , COST(1000) , HI(1000) , LO(1000)
      COMMON  FLOW(1000) , PI(1000)
      COMMON  NODES , ARCS
      COMMON  REINIT(1000) , RETERM(1000) , STORE(500)
      COMMON LAB(25),EPS(25),CAP(25,25),FLO(25,25),SCAN(25),NICID(25,25)
      DIMENSION  NA(1000) , NB(1000)
      COMMON/DATA/ ITLE(20)
      INTEGER ARCS,COST,HI,LO,FLOW,PI
      INTEGER SCAN
      REAL LOW
      LOGICAL NICID,KK
      IIN=5
      IOT=6
      IF(IWHR.EQ.1) GO TO 100
      IF(IWHR.EQ.3) GO TO 104
      IF(IWHR.EQ.4) GO TO 300
      WRITE(IOT,32)
      WRITE(IOT,321)(ITLE(I),I=1,20)
      GO TO 101
100   WRITE(IOT,3)
      WRITE(IOT,321)(ITLE(I),I=1,20)
101   GO TO (10,20,30,40),K
10    WRITE(IOT,4)
      GO TO 990
20    WRITE(IOT,5)
      GO TO 990
30    WRITE(IOT,8)
      GO TO 990
40    WRITE(IOT,31)
81    FORMAT(1H0,30HSTATUS OF NETWORK AT BREAKTHRU  )
990   FLOMAX=0.0
      IF(IWHR.EQ.2) GO TO 200
      WRITE(IOT,6)
      DO 992 I=1,NN
      DO 991 J=1,NN
      IF(.NOT.NICID(I,J))GOTO991
      WRITE(IOT,7) I,J,CAP(I,J),FLO(I,J)
      IF(J.EQ.NN) FLOMAX=FLOMAX+FLO(I,J)
991   CONTINUE
992   CONTINUE
      WRITE(IOT,2) FLOMAX
2     FORMAT(1H0,36HMAXIMUM FLOW THROUGH ABOVE ARCS IS =,F12.4)
3     FORMAT(1H1,16HMAX-FLOW/MIN-CUT,40X,18H***WOOLSEYS WEB***,40X,16HMA
     1X-FLOW/MIN-CUT   )
32    FORMAT(1H1,13HOUT-OF-KILTER,43X,18H***NETWORK FLOW***,43X,13HOUT-O
```

```
      IF(KILTER  )
    4  FORMAT(1H0,22H STATUS OF NETWORK AT START)
    5  FORMAT(1H0,38H STATUS OF NETWORK AT OPTIMAL SOLUTION)
    6  FORMAT(1H0,13HSTARTING NODE,2X,11HENDING NODE,2X,8HCAPACITY,13H  F
   1LOW IN ARC    )
    7  FORMAT(1H0,3X,I10,3X,I10,F10.2,3X,F10.2)
    8  FORMAT(1H0,43H STATUS OF NETWORK AT A FEASIBLE SOLUTION       )
       RETURN
C      OUTPUT ROUTINE FOR SHORTEST PATH ALGORITHM
  104  WRITE(IOT,33)
       WRITE(IOT,321)(ITLE(I),I=1,20)
       GO TO (1041,1040),K
 1040  WRITE(IOT,42)KK
       GO TO 1042
 1041  WRITE(IOT,41)KK
 1042  WRITE(IOT,34)
       J=1
       DO 1043 I=2,NN
 1043  WRITE(IOT,7)J,I,CAP(I,KK)
       GO TO(1045,1044),K
 1044  WRITE(IOT,33)
       WRITE(IOT,321)(ITLE(I),I=1,20)
       WRITE(IOT,43)
       WRITE(IOT,44)
   44  FORMAT(1H0,13HSTARTING NODE,2X,11HENDING NODE,2X,10HARC LENGTH)
 1051  DO 108 I=1,NN
       DO 107 J=1,NN
       KX=NICID(I,J)
       IF(I.GT.J)KX=NICID(J,I)
       IF(KX.AND.(.TRUE.)) GO TO 107
       R=FLO(J,I)
       IF(J.GT.I) R=FLO(I,J)
       IF(ABS(CAP(I,KK)-CAP(J,KK)).NE.R  ) GO TO 107
       IF(I.LT.J) WRITE(IOT,7)I,J,FLO(I,J)
  107  CONTINUE
  108  CONTINUE
 1045  RETURN
  331  FORMAT(1H1,21HMINIMAL SPANNING TREE,35X,18H***WOOLSEYS WEB***,35X,
   121HMINIMAL SPANNING TREE)
   34  FORMAT(1H0,13HSTARTING NODE,2X,11HENDING NODE,2X,8HDISTANCE)
   41  FORMAT(1H0,32H STATUS OF NETWORK AT ITERATION ,I2)
   42  FORMAT(1H0,40H STATUS OF NETWORK AT OPTIMUM, ITERATION ,I2)
  431  FORMAT(1H0,57HTHE MINIMAL SPANNING TREE CONSISTS OF THE FOLLOWING
   1ARCS  )
C      OUTPUT ROUTINE FOR OUT OF KILTER
  200  WRITE(IOT,201)
  201  FORMAT(1H0,13HSTARTING NODE,2X,11HENDING NODE,9X,4HCOST,2X,11HUPPE
   1R BOUND,2X,11HLOWER BOUND,2X,11HFLOW IN ARC   /
   2 14H   NODE    NO. , 2X , 11H NODE   NO.   )
       DO 202 I=1,ARCS
       CST = COST(I)
       HIGH = HI(I)
       LOW = LO(I)
       FLOO= FLOW(I)
       CST = CST / 100.
       HIGH = HIGH / 10.
       LOW = LOW / 10.
       FLOO= FLOO/ 10.
  202  WRITE(IOT,203)REINIT(I) , N(I) , RETERM(I) , N(I) ,
   1                  CST , HIGH , LOW , FLOO
  203  FORMAT(1H0,2(2X,A4,3X,I4) , 4(3X,F10.2))
       WRITE(IOT,32)
       WRITE(IOT,321)(ITLE(I),I=1,20)
       WRITE(IOT,204)
  204  FORMAT(1H0,19HPI VALUES FOR NODES )
       WRITE (IOT,205)
  205  FORMAT(1H0,3X , 4HNODE , 10X , 3HNO. , 9X , 8HPI(NODE) )
       DO 207 I=1,NODES
  207  WRITE(IOT,206)STORE(I) , I , PI(I)
  206  FORMAT(1H0,3X , A4 , 2(3X,I10))
       RETURN
C      OUTPUT ROUTINE FOR MINIMAL SPANNING TREE
```

```
120       300   WRITE(IOT,331)
121             WRITE(IOT,321)(TITLE(I),I=1,20)
122             WRITE(IOT,431)
123             WRITE(IOT,34)
124             DO 302 I=1,NN
125             DO 302 J=1,NN
126             IF(I.GT.J) GO TO 302
127       C     IF(NICID(I,J).EQ.2) WRITE(IOT,7)I,J,FLO(I,J)
128       302   CONTINUE
129             RETURN
130       33    FORMAT(1H1,13HSHORTEST PATH ,43X,18H***WOOLSEYS WEB***,43X,13HSHOR
131            1TEST PATH  )
132       43    FORMAT(1H0,62HTHE SHORTEST PATHS FROM ARC ONE CONSISTS OF THE FOLL
133            1OWING ARCS      )
134       321   FORMAT(1H0,20A4)
135             END
```

Note: Max Flow/Min Cut and Shortest Path subroutines are not shown since they were not used in this study.

Appendix D

VERIFICATION OF CALCULATIONS AT OPTIMUM SOLUTION

In this appendix, selected unit costs from the computer printout sheet shown in Table 5-2 are verified by hand calculations to illustrate their validity. The procedure used in making these calculations is discussed in detail. Finally, the total annual cost shown in Table 5-3 is verified by hand calculations.

BASIC INPUT DATA – UNIT COST CALCULATIONS

Table 5-3 contains a listing of basic problem data along with the unit cost for each network arc computed by the preprocessing program. From this table, three arcs (S1-S1A, D1-D1A, and R1-R1B) have been selected and their unit costs calculated by hand to verify the computer calculations. The cost vs flow rate functions presented in Section 4 of this report were used to make these calculations along with the following equation (see Section 4).

$$C = a\,Q^{-b} \qquad (1)$$

where

$$b = \frac{\log (C_1/C_2)}{\log (q_2/q_1)}$$

$$a = \frac{C_1}{q_1^{-b}}$$

Values for C_1, C_2, q_1, and q_2 used in the computer program, as shown in the program listing in Appendix C, were used with the above equation to determine the constants "a" and "b."

An example of the type of calculations made can be seen by referring to line 145 on page C-4 of the Computer Program listings, which reads:

CAS = CALC (20.9, 7.4, 1.0, 100.0, ASMFLO)

where

CAS = Cost of primary plus activated sludge treatment
20.9 = Unit cost (cents/1000 gal) at 1.0 mgd flow
7.4 = Unit cost (cents/1000 gal) at 100.0 mgd flow
CALC = Program Terminology
ASMFLO = Program Terminology

By substituting the above unit costs into Equation 1, the constant "b" can be calculated as follows:

$$b = \frac{\log (20.9/7.4)}{\log (100/1.0)} = \frac{0.452}{2} = 0.226$$

The constant "a" can now be calculated:

$$a = \frac{20.9}{(1.0)^{-0.226}} = 20.9$$

Therefore, the unit cost equation for primary plus activated sludge is as follows:

$$C = 20.9\ q^{-0.226}$$

For a flow of 25 mgd, the unit cost is:

$$C = 20.9\ (25.0)^{-0.226} = 10.05 \text{ cents/1000 gal}$$

This hand-calculated unit cost is in excellent agreement with the value of 10.0 cents/1000 gal, read from Figure 4-3.

Shown in Table D-1 are the flows, hand-calculated values for the constants "a" and "b," and the hand-calculated unit costs for the three arcs selected to verify the computer calculations. Also shown in this table are the unit costs for the same arcs as calculated by the computer and presented earlier in Table 5-2. It can be seen that for each of the three arcs tested, the hand-calculated unit cost values are in excellent agreement with the computer values.

NETWORK AT OPTIMAL SOLUTION – TOTAL COST CALCULATION

The status of the network at the optimal solution was presented earlier in Table 5-3. Shown in this table are the flows in each arc at the optimal solution and the unit cost for each arc. Also shown is the total annual cost of the system at $10,478,829. The objective of the following presentation is to verify this total annual cost value.

From the data generated by the computer as shown in Table 5-3, the following calculation was made:

$$\text{Daily Cost (\$)} = C \times q \times 10$$

where

C = Unit cost (cents/1000 gal) for each arc in the optimal solution

q = Flow rate (mgd) for each arc in the optimal solution

The daily costs calculated for each arc were then summed and converted to total annual cost. These calculations are shown in Table D-2. A value of $10,477,186 was obtained for this hand calculation, which is

very close to the computer value of $10,478,829. The slight difference in these values can be attributed to the loss of significant figures in the hand calculation. Based on this information, verification of the total annual cost calculation made by the computer has been made.

Table D-1

VERIFICATION OF UNIT COSTS

Arc		Q	Process	Cost vs. Flow Function						Unit Cost, ¢/1000 gal		Fig. No. Sect. 4	Comments
				Basic Input Data				Coef.	Exp.	Unit Cost	Computer		
Initial Node	Terminal Node	Assumed Flow, mgd[1]		C_1	C_2	q_1, mgd	q_2, mgd	a	b	C	Value		
S1 (1)	S1A (2)	18.4	CSUPM							20.0	20.0		Source development and conveyance in groundrules
			CSWTR	8.0	5.3	10.0	100.0	12.08	.179	7.16	7.2	4-1	Surface water treatment without so
			CSTOR	.18	.15	10.0	100.0	.217	.080	.18	.2	4-6	Treated water storage
								Total		27.34	27.34		
D1 (5)	D1A (6)	24.3	CSD	66.0	47.5	5.0	100.0	78.70	.110	55.5	55.5	4-2	Seawater distillation
								Total		55.5	55.48		
R1 (8)	R1B[2] (9)	0.5[3]	CPNC	57.4	21.8	1.0	10.0	57.90	.420	76.8	76.8	4-4	Phosphorus, nitrogen, and carbon fi
			CED	23.7	10.2	1.0	100.0	23.70	.183	26.9 *5.00	31.9	4-4	Electrodialysis *Increase reflects latest cost inform
			CSTOR	1.48	.18	.1	10.0	.505	.457	.70	.7	4-6	Treated water storage
								Total		109.40	109.44		

Notes: 1. Flows shown are from the iterative procedure.

2. Arc R1-R1B was not used in the optimum solution.

3. For Q $\leq$ 0.5 mgd, a flow rate of 0.5 mgd is used in the unit cost calculation.

Table D-1

VERIFICATION OF UNIT COSTS

Q Assumed Flow, mgd[1]	Process	Cost vs. Flow Function: Basic Input Data C_1	C_2	q_1, mgd	q_2, mgd	Coef. a	Exp. b	Unit Cost, ¢/1000 gal: Unit Cost C	Computer Value	Fig. No. Sect. 4	Comments
18.4	CSUPM							20.0	20.0		Source development and conveyance – Cost given in groundrules
	CSWTR	8.0	5.3	10.0	100.0	12.08	.179	7.16	7.2	4-1	Surface water treatment without softening
	CSTOR	.18	.15	10.0	100.0	.217	.080	.18	.2	4-6	Treated water storage
						Total		27.34	27.34		
24.3	CSD	66.0	47.5	5.0	100.0	78.70	.110	55.5	55.5	4-2	Seawater distillation
						Total		55.5	55.48		
0.5[3]	CPNC	57.4	21.8	1.0	10.0	57.90	.420	76.8	76.8	4-4	Phosphorus, nitrogen, and carbon filtration
	CED	23.7	10.2	1.0	100.0	23.70	.183	26.9 *5.00	31.9	4-4	Electrodialysis *Increase reflects latest cost information
	CSTOR	1.48	.18	.1	10.0	.505	.457	.70	.7	4-6	Treated water storage
						Total		109.40	109.44		

s shown are from the iterative procedure.

R1-R1B was not used in the optimum solution.

Q ≤ 0.5 mgd, a flow rate of 0.5 mgd is used in the unit cost calculation.

Table D-2

VERIFICATION OF ANNUAL COSTS

Starting Node	Starting No.	Ending Node	Ending No.	Cost cents/1000 gal	Arc Flow (mgd)	Daily Costs $
S1	1	S1A	2	27.34	18.40	5,030.56
S1A	2	M1	18	4.61	18.40	848.24
S2	3	S2A	4	27.88	12.30	3,429.24
S2A	4	M2	19	5.51	12.30	677.73
D1	5	D1A	6	55.48	24.30	13,481.64
D1A	6	M1	18	6.19	11.60	718.04
D1A	6	M2	19	7.71	7.70	593.67
D1A	6	I2B	21	4.27	5.00	213.50
R1A	7	R1	8	11.34	15.00	1,701.00
R1	8	I1	20	5.05	10.00	500.50
R1	8	E1	16	0	5.00	0
R2A	10	R2	11	12.43	10.00	1,243.00
R2	11	E2	17	0	5.00	0
R2	11	A1	22	5.35	5.00	267.50
Total Daily Cost						28,704.62
Total Annual Cost (28,704.62 x 365)						10,477,186
Computer Value						10,478,829

Appendix E

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